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Can urban greening counterbalance the dynamic impacts of urbanisation?

by Ashley Naomi Jane Douglas

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Assoc Prof Fraser R. Torpy and Dr Peter J. Irga

University of Technology Sydney
Faculty of Science
School of Life Sciences

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Certificate of Original Authorship

I, Ashley Naomi Jane Douglas declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Life Sciences, Faculty of Science at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

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Statement Of Thesis Format And Author Contributions

This thesis is submitted as a thesis by compilation. This thesis consists of seven chapters. Chapters 2, 4, and 6 represent separate articles, all of which have been peer-reviewed, accepted and published in scientific journals. As such, parts of this thesis are presented verbatim to their published form; consequently, some repetition occurs in regards to themes and style.

To prevent unnecessary duplication, a single reference list has been provided at the end of the thesis.

This thesis is a compilation of my own work with guidance from my supervisors and additional assistance from others. I conceptualized my research, designed the experiments including choice of methods and instrumentation, conducted the data collection and analysis, and wrote the manuscripts.

My supervisors and co-authors supported my research, and proof-read and edited the final peer reviewed manuscript versions. Publication details and co-authors are detailed below. Co-authors have provided their signatures to confirm their contribution in their respective publications. Associate Professor Fraser Torpy and Dr Peter Irga formed my supervisory panel (indicated with an asterix (*)).

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Douglas, A.N.J., Irga, P.J. & Torpy, F.R. (2019) Determining broad scale associations between air pollutants and urban forestry: A novel multifaceted methodological approach, *Environmental Pollution*, vol. 247, pp. 474-81 https://doi.org/10.1016/j.envpol.2018.12.099

Irga, P.J., Pettit T., Irga, R.F., Paull, N.J., **Douglas, A.N.J.** & Torpy, F.R. (2019) Does plant species selection in functional active green walls influence VOC phytoremediation efficiency? *Environmental Science and Pollution Research* https://doi.org/10.1007/s11356-019-04719-9

Douglas, A, Torpy, F, Surawski, N & Irga, P (2018) Mapping Urban Aerosolized Fungi: Predicting Spatial and Temporal Indoor Concentrations, *Human Ecology Review*, vol. 24, no. 2, pp. 81-104 https://www.jstor.org/stable/26785907

Irga PJ, Braun JT, **Douglas ANJ**, Pettit T, Fujiwara S, Burchett M, Torpy FR (2017) The distribution of green walls and green roofs throughout Australia: Do policy instruments influence the frequency of projects. *Journal of Urban Forestry and Urban Greening*, 24, 164-174 https://doi.org/10.1016/j.ufug.2017.03.026

Conference Presentations And Posters During My Candidature

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F Torpy, P Irga, R Fleck, S Matheson, H Smith, G Duani, N Surawski, **A Douglas**, L Lyu (2022) Phytoremediation of air pollution. 26th International Clean Air and Environment Conference. 14/09/2022, online.

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Douglas ANJ, Irga PJ, Torpy FR (2018) A competitive model for determining air pollution in urban areas: The establishment of the spatial relationship between urban forestry and air pollution mitigation. International Urban Forestry Congress 2018. 30/9/2018 - 3/10/2018, Vancouver, BC, Canada.

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2023 - Nominated NSW representative for the overall CASANZ National Student Award

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2018 - Higher Degree Research Science Faculty Travel Scholarship, University of Technology Sydney

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1. Underlying Motivations For This Work

The impacts of urbanisation are inescapable. Already 55% of the world's population are feeling the impacts of urbanisation and that is set to increase as urban areas are expanding faster than any other land-use type [1-3]. The UN predicts 70% of world's population will be living in urbanised areas by 2050 [4] despite cities and urbanised areas only accounting for 3% of the Earth's cover.

Consequently, urban expansion has resulted in more than 80% of natural habitat loss in local areas [4]. The loss of green space also comes with increased air pollution, elevated levels of noise pollution, loss of biodiversity and the Urban Heat Island effect and these impacts do not discriminate. They are already being felt globally and are set to continually increase in the future. For example, in 2021, 99% of the world's urban population lived in areas that exceeded the new air quality guidelines set by the World Health Organization [5].

These negative impacts also have secondary effects. Ambient air pollution from traffic, industry, power generation, and alike was associated with 4.2 million premature deaths in 2019 [6]. Moreover, the combined impact of ambient air pollution and household air pollution was associated with 6.7 million premature deaths every year [6]. Subsequently, the increases in associated health complications place pressure on infrastructure. In 2015, global economic burden linked with premature deaths from outdoor air pollution was estimated to be approximately $3 trillion USD and that is predicted to rise to $25 trillion by 2060 [7].

The Urban Heat Island effect is responsible for increased energy consumption due to a greater demand for temperature regulation usually through cooling. Consequently, urbanised areas account for up to 80% of the world's energy consumption and approximately 75% of it's carbon emissions [4].

Ultimately, the realities of urbanisation and associated negative impacts is of such a concern that the United Nations incorporated them into their Sustainable Development Goals. These goals are key in addressing the impacts associated with urbanisation and these goals are interwoven throughout my research as they are particularly pertinent to my study area, Australia. Australia is predicted to suffer the impacts of urbanisation to an even greater extent as the 86% of Australia's population is already residing in urbanised areas and that is predicted to increase to 91% by 2050 [8]. Furthermore, Australia's population surpassed 27 million approximately 20 years earlier than predicted [9].

Despite the current realities faced by mankind, research suggests a commonly proposed solution could address multiple issues simultaneously in the form of green infrastructure and urban forestry. Urban forestry and green infrastructure refer to the integration of vegetation in the urban environment [10]. It could be in the form of free stand patches of vegetation such trees, parks, green streetscapes to integration of vegetation in into building design, including green wall and green rooves both indoors and outdoors (Figure 1.1).

Figure 1.1 – Examples of urban forestry and green infrastructure (Douglas 2020).

There is a diverse range of benefits from the incorporation of urban forestry and green infrastructure. Urban forestry provides a multitude of benefits, including mitigating the Urban Heat Island effect, lowering energy usage, improved air quality, fostering biodiversity, improving storm water management, reducing noise pollution, boosting urban food production and enhancing social, psychological and biophilic satisfaction [11-29].

Despite the numerous advantages, urban areas often face space constraints, as green spaces contend with other land uses and socioeconomic priorities. Additionally, the reduction or removal of vegetation is rarely compensated or offset appropriately within developing cityscapes [30]. To address these challenges, cities and countries worldwide have been researching, supporting, and implementing urban forestry and green infrastructure projects over the past several decades, with more of the uptake occurring across Asia, Northern America, and Western Europe. For example, Singapore is one of the most greened cities in the world with 50% green cover equating to 72 hectares of green walls and green roofs [31]. It does this through various incentives such as the Skyrise Greenery Incentive Scheme, which funds up to 50% of the costs of installation of green roofs. Stuttgart, Germany, has famously employed a combination of urban forestry policies and subsidies since 1986, making it one of Europe's most densely forested cities [32].

On the contrary, Australia has seen less frequent adoption of urban forestry and green infrastructure. Several constraining factors contribute to this, including the absence of standards for construction, installation and maintenance; a limited pool of potential installers or suppliers leading to problems with isolated supply chains; inadequate awareness and a lack of compelling examples and case studies, which undermines confidence among builders, urban designers, green stakeholder or the general public regarding green initiatives; insufficient government support in terms of policies, regulations, green standards, financial incentives and funding; and an absence of Australian research [33, 34]. Most of the evidence, information, case studies, and research that highlights urban forestry's positive effects and encourages green infrastructure implementation is predominantly from Europe, North America and Asia.

The lack of Australian-centric research plays a vital part in our resistance to urban greening. Furthermore, the impacts of urbanisation are insidious and lethal, as air pollutant claims over ten times the number of lives annually compared to the Australian road toll [35]. The lack of Australian centred research acts as a prominent barrier and creates a significant gap in knowledge due to differences in temperature, rainfall, and suitable vegetation, particularly as the success of these green projects is dependent on the climate-specific plant selection, resilience, and maintenance [34]. This is further compounded by Australia’s long distances between cities, with our capital cities experiencing drastically different climates as Australia experiences six different climatic zones in one country, from tropical climates to arid deserts [36].

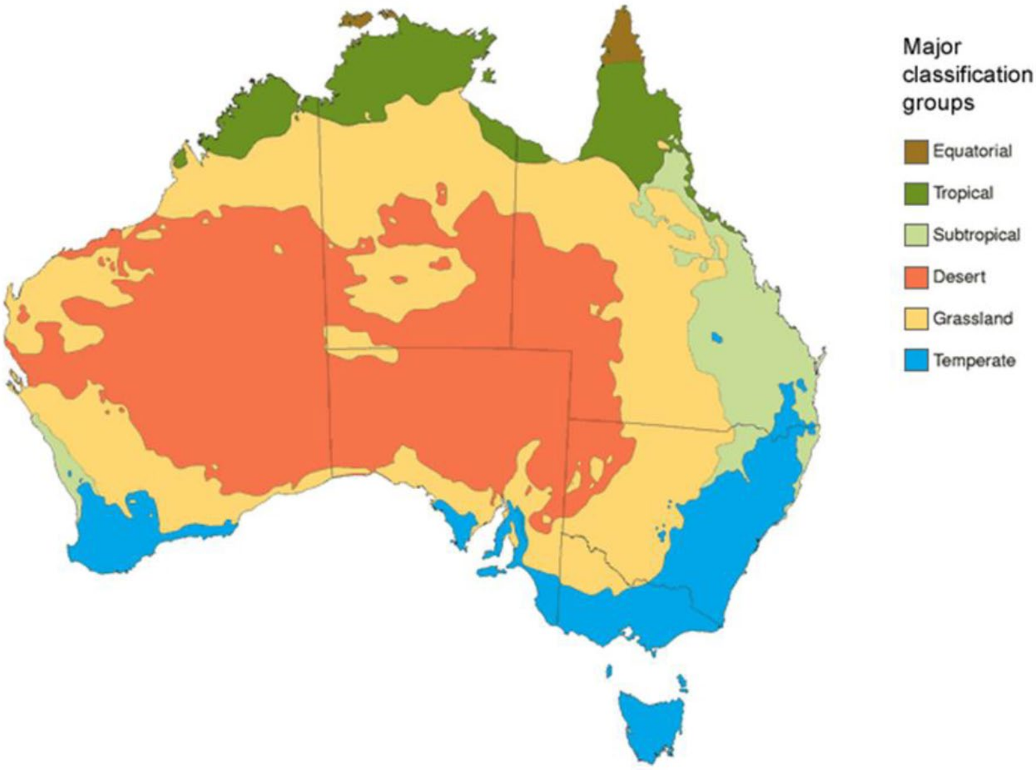

Figure 1.2 - Climate zones in Australia based on the Köppen classification system [37].

Thus, to address these issues and the gaps in knowledge currently in Australia, this work focused on using interdisciplinary methods and incorporating a holistic approach by bringing different research topics together to create this body of work and subsequently converting theoretical knowledge into practical application (Figure 1.3). Firstly, the two of the most prominent issues associated with urban environments, air pollution and noise pollution, and their relationships with urban greenery and urban land uses were investigated in Chapters 2 and 3, respectively, to better understand what we will face as a society. These chapters established the inverse relationships between these urban pollutants and different forms of green infrastructure to both introduce and highlight the potentially significantly positive impact of nature based solutions.

Following that, an investigation into the impact of two major events on air pollution was conducted to elucidate further the spatial and temporal factors associated with the negative impacts of urbanisation. This chapter, Chapter 4, highlighted the need for dynamic and proactive solutions and approaches if we are address these issues in a meaningful manner as the negative impacts associated with urbanisation are not static by nature.

The focus shifted for the remaining two chapters, Chapters 5 and 6, from understanding the issues and the potential solutions to acceptability and implementation of these solutions, as these are key when it comes to counterbalancing the dynamic impacts of urbanisation. Specifically, Chapter 5 focused on investigating the social acceptability and willingness to implement green infrastructure in the form of green walls, while Chapter 6 investigated the implementation and feasibility of green walls uptake through the development of an analytical method that is accessible to all.

Consequently, the specific aims for this body of research are as follows:

1. Investigate the relationship between air pollution and land use, land cover, and urban forestry to understand the potential associations between vegetation and air quality.
2. Investigate the effectiveness of vegetated green wall modules for noise pollution mitigation through sound absorption.
3. Investigate the impact of two significant events on outdoor ambient air pollution to elucidate dynamic factors affecting air pollution across a cityscape.
4. Investigate the social acceptability of green infrastructure, in particular green walls, by investigating the general public's awareness, experience, and perception of green walls, barriers to implementation, and willingness to pay for local green wall development.

5. Investigate the implementation and feasibility of green walls retrofitability in highly urbanised areas through the development of an analytical tool for preliminary assessment.

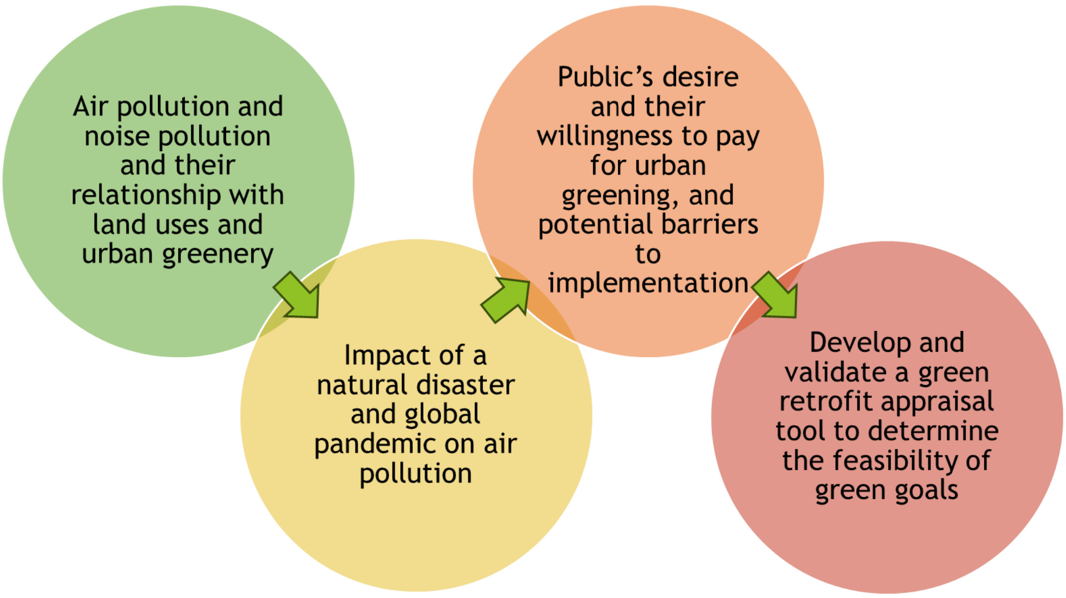

Figure 1.3 – The investigations in question create this multifaceted and interdisciplinary body of work to determine if urban greening can counterbalance the dynamic impacts of urbanisation.

2. Investigating Vegetation Type Based On The Spatial Variation In Air Pollutant Concentrations Associated With Different Forms Of Urban Forestry.

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Keywords

Air pollution; Vegetation types; GIS; Land use; Land cover; Urban forestry

Abstract

Globally, rapid urbanisation is one of the major drivers for land use changes, many of which have a marked impact on urban air quality. Urban forestry has been increasingly proposed as a means of reducing airborne pollutants; however, limited studies have comparatively assessed land use types, including urban forestry, for their relationship with air pollution on a city scale. We thus investigated the spatial relationships between three air pollutant concentrations, NO_2, SO_2, and PM_{10}, and different land uses and land covers across a major city, by constructing a yearly average model combining these variables. Additionally, relationships between different vegetation types and air pollutant concentrations were investigated to determine whether different types of vegetation are associated with different air pollutants. Parklands, water bodies, and more specifically, broadleaf evergreen forest and

mangrove vegetation were associated with lower pollutant concentrations. These findings support urban forestry's capabilities to mitigate air pollution across a city-wide scale.

Introduction

As global urban population growth increases, there is a concomitant need to quantify the impacts of urbanisation — with one of the most pressing issues being air pollution. Urban air pollution has a direct impact on human health [38]; outdoor air pollution is responsible for approximately 4.2 million premature deaths globally each year [39], and global welfare costs associated with premature deaths from outdoor air pollution have been estimated to be $3.5 trillion USD and rising [40]. Consequently, as evidence for the negative impacts of air pollution on human health and the global economy continues to increase, improving urban air quality has become one of the most pressing tasks facing today [41].

Although reducing air pollutant emissions at the source is to be the most effective way to improve air quality [42, 43], urban forestry and other forms of urban greening have been proposed as means to reduce atmospheric pollution levels [44, 45]. The mechanisms associated with urban forestry-mediated air pollution reduction are well documented at the individual tree level, with gaseous air pollutants such NO_2 and SO_2 absorbed through the stomata into the leaf interior [46-48], and particulate pollution captured and removed from the atmosphere by dry deposition on plant surfaces [49-51].

The potential for air pollution removal by vegetation notwithstanding, there are few studies that assess the associations between urban forestry and air pollution on a city scale, accounting for factors such as variations in the types of vegetation and functions of existing urban green areas [52]. This gap in knowledge could be a consequence of the complexity of physiochemical vegetation-atmosphere interactions, which are particularly challenging within urban areas [53]. Geographical Information Systems (GIS) have significant potential for evaluating these relationships, with GIS increasingly employed to model and assess the extent and impact of air pollution in urban areas [45]. Further, the incorporation of exploratory models enables relationships to be statistically evaluated [54], not only enabling the characterisation of the air pollutant - urban forestry relationship relative to competing activities such as anthropogenic sources and sinks, but also to determine the corresponding pollutant loading based on different vegetation types, potentially enabling them to be compared with respect to pollutant efficiency at an entire forest level.

Addressing these knowledge gaps would support urban planners and green stakeholders by offering a greater understanding for more effective and adaptive nature based solutions to space-constrained urban areas. It would also broaden their insight into the interacting impacts of anthropogenic sources and sinks, allowing for more informed infrastructure and planning decisions.

Here, we present the development of high-resolution city-scale exploratory models to analyse the spatial distribution of concentrations of NO_2, SO_2 and PM_{10}, and compare spatially related parameters of potentially contributing sources and mitigating sinks. The objectives of this paper were to: (1) determine spatio-periodicity for the urban air pollutant concentrations; (2) build a database of industrial and traffic emissions as contributing factors, and specify what accounts for both urban spatial effects and the simultaneous effects of these factors; (3) assess how these effects vary across the study area, with respect to the prevailing land use zoning and urban forestry types present; (4) investigate the land use types that are best for air pollutant model estimation; and (5) based on significant associations, investigate the urban forestry types with lower urban air pollutant concentrations.

Materials And Methods

1. Study area

This study focused on the Greater Sydney region as Sydney is the most populated city in Australia, with more than 5 M people [55]. Consequently, Sydney has a higher dwelling and population density, and a greater degree of urbanization compared to other Australian cities [56-60]. Sydney is situated along the mid-coast of New South Wales on a lowland plain between the Pacific Ocean to the east and elevated sandstone tablelands to the north, south, and west, creating the Sydney Basin [61]. Greater Sydney covers approximately 12,400 km^2 and the profile of this basin has previously been associated with the transportation and accumulation of air pollutants produced within the area [62-64], thus making air quality a key concern for this international city. Additionally, Sydney is a complex mosaic of numerous anthropogenic activities, such as commercial, industrial and agricultural, contributing to the accumulation of ambient air pollution, intersperse with natural areas, such as parklands and water bodies [59, 60, 65-68].

2. Data preparation

2.1. Ambient air pollutant concentrations

Ambient daily air pollutant concentrations for NO_2, SO_2, and PM_{10} were incorporated in this study. The data was sourced from the NSW Government's Department of Planning and Environment (DPE) monitoring network, which has air quality monitoring stations at 20 sites covering the entire Sydney basin region [69-71]. Each monitoring station records air quality data hourly, in accordance with the National Environment and Protection Measures which is a national set of legally binding standards for air quality monitoring across Australia.

2.2. Industrial pollutant concentrations

Point source industrial pollutant concentrations for NO_2, SO_2, and PM_{10} were incorporated in this study. In Australia, there is a national scale database for reporting and monitoring industrial pollutant concentrations, named National Pollutant Inventory (NPI), which reports 93 substances [72]. It is managed by the Australian Government and monitors industrial facilities who have previously exceeded Australia's legally binding air pollution thresholds [72]. Despite the wide range of NPI pollutant data and their public availability, the NPI data has been underutilised in research areas, particularly for analysing ambient air pollution. Thus, NPI pollutant data from 168 NPI monitored sites within and surrounding Sydney were used for each air pollutant was incorporated in this study (Figure 2.1). The NPI uses NO_x as a surrogate for NO_2 emissions, as NO_x is conventionally expressed as a NO_2 mass equivalent, and NO_2 is the most predominant form of atmospheric NO_x [73].

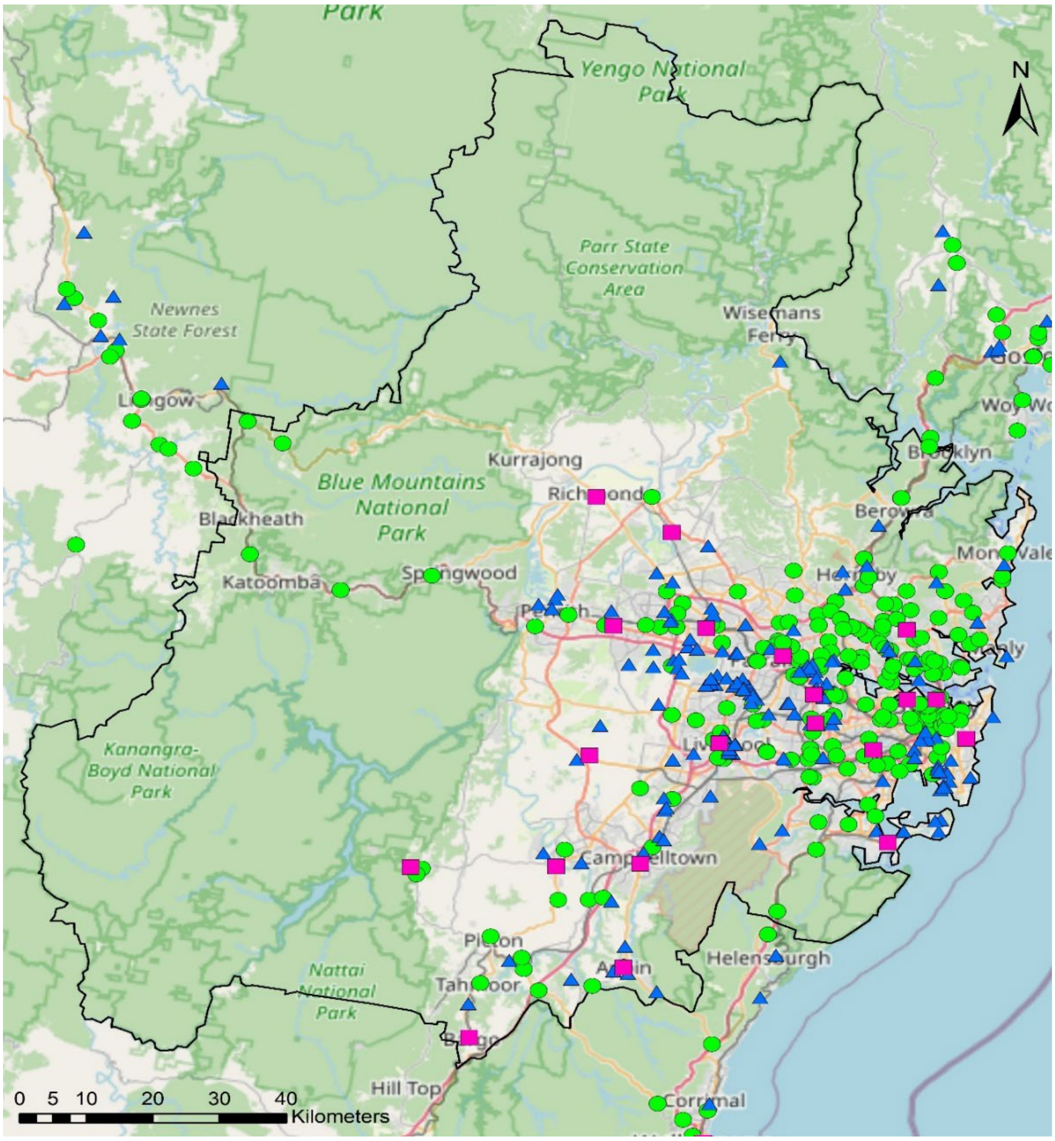


Figure 2.1 - The NSW DEP monitoring sites represented by pink squares [69-71]. The blue triangles represented the National Pollutant Inventory industrial locations [72]. The traffic data collection points represented by the green circles [74].

2.3. Land Use Cover

Land use data consisted of planning and zoning data provided by the *Australian Bureau of Statistics*, which categorised land use types into 11 different definitions during the 2006 Australian Census. Despite this data originating from the 2006 Australia Census, the data retained a high degree of accuracy and temporal relevance to the 2008 study period, as it was updated in August 2007 [75]Table 2.1, Figure 2.2].

Table 2.1. Land use data types provided by the Australian Bureau of Statistics during the Australian Census [75].

Land Use	Parameters for Land Cover
Agricultural	Agricultural activities e.g. farming
Commercial	Areas of business, no usual residences or dwellings, e.g. shopping malls.
Educational	Institutions, e.g. schools or universities, that may contain a residential population in non-private dwellings such as student accommodation.
Hospital and medical	Facilities such as hospitals and medical centres
Industrial	Areas of industry, no usual residences or dwellings, e.g. factories.
Commonwealth land	Land that did not fit into other categories such as Defence sites and Commonwealth owned and operated lands.
Parkland	Any public space, sporting arena or outdoor facility e.g. racecourses, golf courses, stadia, nature reserves and other protected or conservation areas.
Residential	Residential development.
Shipping	Related to shipping activities, e.g. ports.
Transport	Road, rail, and air transportation infrastructure
Water bodies	Artificial and natural water bodies that were not entirely enclosed by another land use, for example, a water body inside a University was not included in this count.

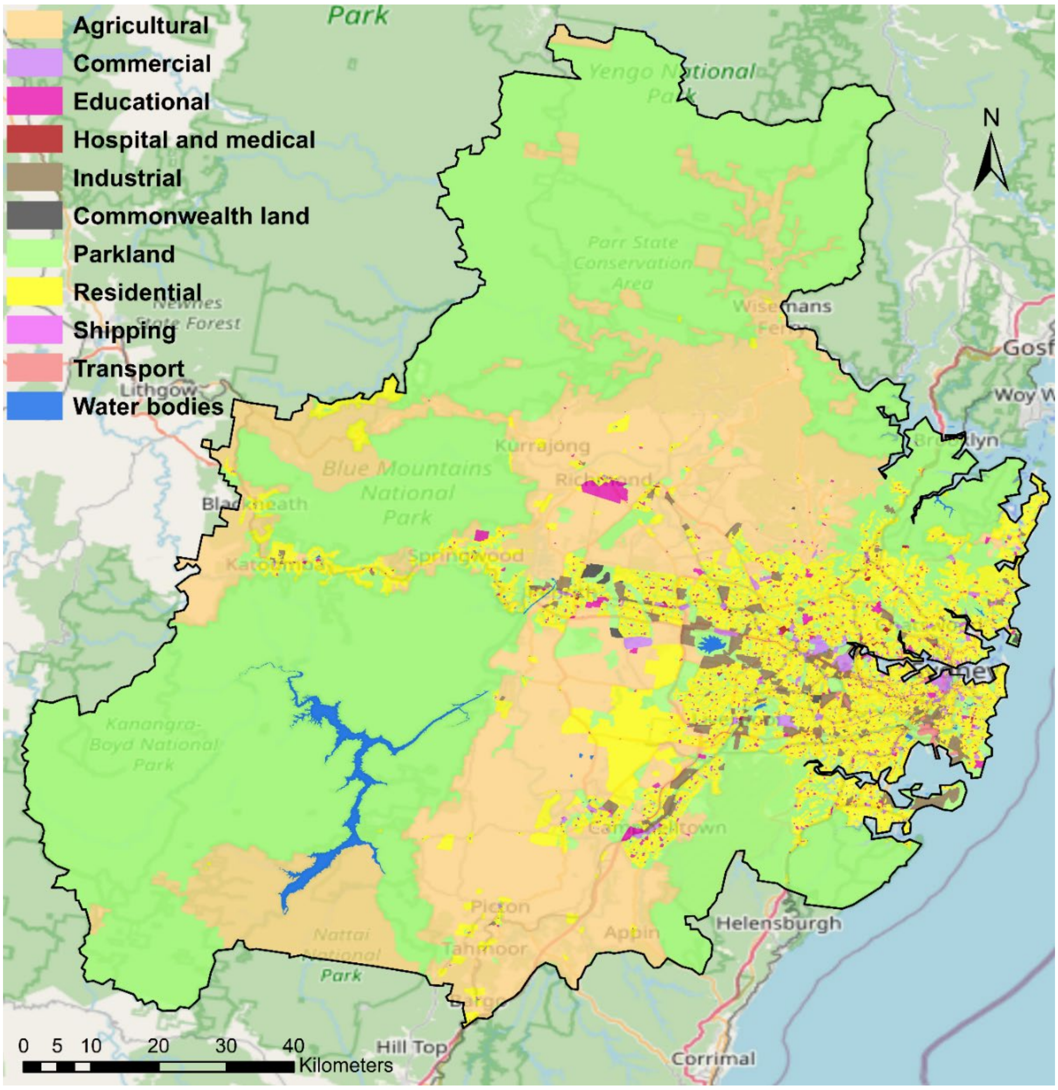


Figure 2.2 - Land use data types provided by the Australian Bureau of Statistics during the Australian Census [75].

2.4. Urban Forestry Cover

Urban forestry cover data was obtained from the Global Mapping Project (GMP), which was developed through the incorporation of MODIS and Landsat data, Virtual Earth, existing regional and local maps, and existing land cover products [76]. The spatially relevant data set included nine vegetation types and two urban land covers, water and artificial surfaces (Figure 2.3, Table 2.2).

Table 2.2. Vegetation types identified in Greater Sydney by the GMP – Forestry Cover data set for 2008 [76].

Land Cover	**Parameters for Land Cover**
Broadleaf evergreen forest	Open to closed, 40 – 100% cover
Needleleaf evergreen forest	Open to closed, 40 – 100% cover
Tree open	Open woodland, 10 – 40% cover
Shrub	Open to closed shrubland and thickets, 40 – 100% cover
Herbaceous	Open to closed herbaceous vegetation as a single layer of vegetation, 40 – 100% cover
Herbaceous with sparse tree/shrubland	Open to closed herbaceous vegetation with trees and shrubs, 40 – 100% cover
Sparse vegetation	Sparse (<40% cover) herbaceous or woody vegetation
Mangrove	Open to closed woody vegetation in a saline water environment, 40 – 100% cover
Cropland	Cultivated areas of herbaceous crops

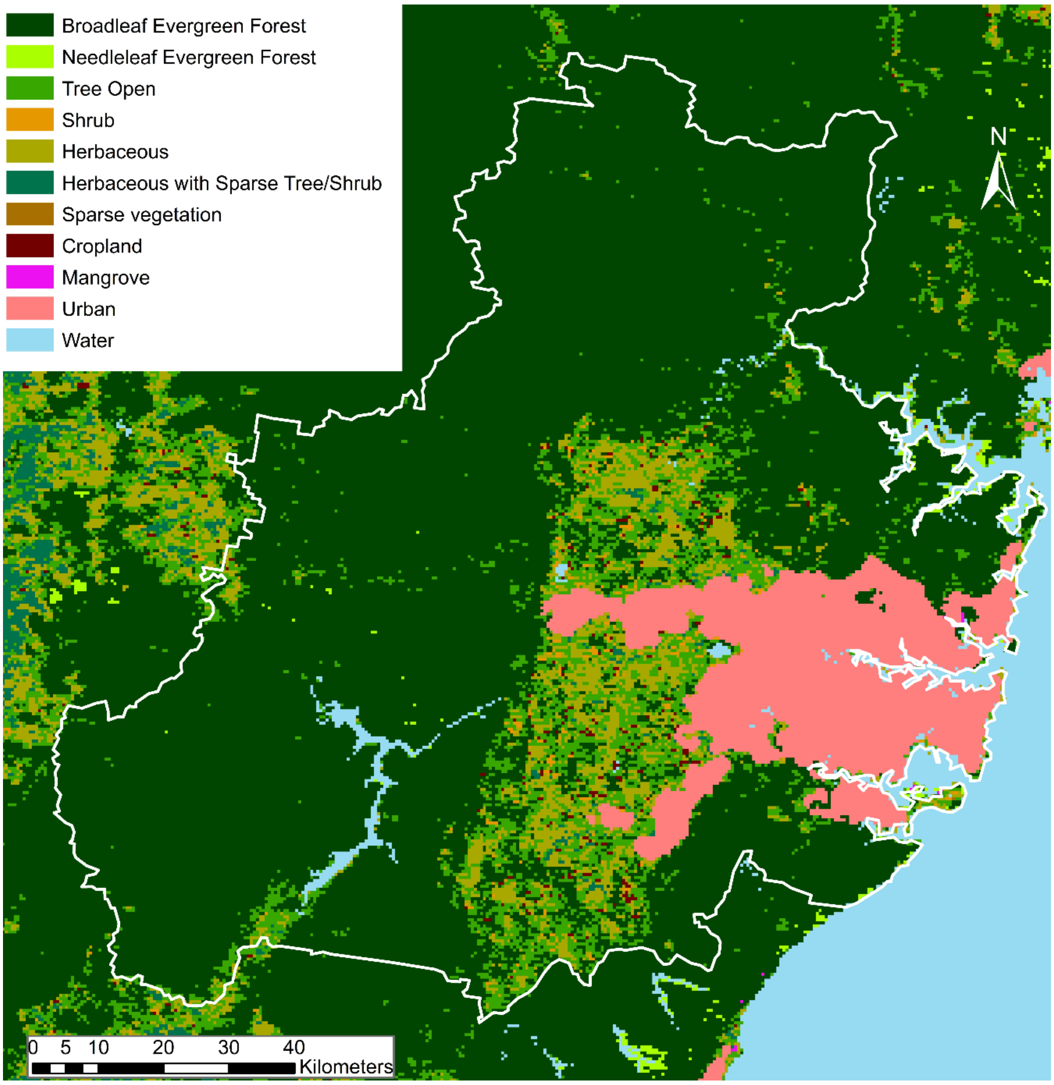


Figure 2.3. The spatially relevant data set included nine vegetation types and two urban land covers, water and artificial surfaces present in Sydney.

2.5. Daily traffic count

The daily traffic count data was used to correct for traffic density and subsequent traffic derived air pollution, with the data from 211 Roads and Maritime Services (RMS) traffic collection sites across Sydney annually averaged for daily traffic count and then spatially interpolated (Figure 2.1). The traffic data included count data for all vehicle types and directions of travel [74].

3. Overlay and analysis

All data was transformed to the Geocentric Datum of Australia 1994 [77] and annually averaged within the same study period, 2008, thus randomising potentially confounding factors such as wildfires, hazard reduction burns, and seasonal and meteorological effects, such as wind, that have been identified in previously published air pollutant studies [45, 62, 78-81]. The sensitivity for this type of investigation is strongly dependent on the spatial resolution of the analyses in order to show clear spatial distributions and trends, identifying associations between air quality, vegetation and other influential variables such as traffic, population density or other anthropogenic activities [82-84]. Thus, a high pixel resolution of 30 m^2 was used for this investigation.

The analytical method applied in this study was based on methods previously established by the European Study of Cohorts for Air Pollution Effects [79, 80] with the incorporation of additional urban metrics and air pollutants. All data was transformed to the same spatial resolution and spatially joined. ArcGIS version 10.3.1 (ESRI Inc., Redlands, USA) was used for all spatial processing, interpolation, transformations, joining, and map creation while statistical processing, analyses, and visualisations were performed in SPSS version 24 (Chicago, IBM SPSS, Inc.) and Microsoft Excel 2016 (Microsoft Corp., Redmond, WA).

General linear model, single factor analyses of covariance (ANCOVAs) were generated and compared for each of the three air pollutants amongst land use and urban forestry types. NPI industrial concentrations and RMS traffic data were incorporated as covariables to correct for air pollutant source. Pairwise comparisons were made using Bonferroni's *post hoc* tests [85] and estimated marginal means (EMMs) were derived from the ANCOVAs to control for the predicted high Type I error rate for the univariate statistical analyses [85-87]. Finally, all univariate contrasts were confirmed through the determination of whether the 95% confidence interval for an EMM overlapped with the EMM of another group.

The first exploratory model utilised the 11 different land use types (Section 2.3) to identify spatial associations between land use and air pollutant concentrations. The second model utilised urban forestry data to identify associations between different vegetation types (Section 2.4) and air pollutant concentrations to facilitate a greater understanding about the potential for different vegetation types influencing pollutant concentrations.

Results

1. The effects of urban land use on air pollutant concentrations

All three air pollutant concentrations were positively and significantly associated with the covariables, traffic density and NPI pollutants (Table 2.3; $p < 0.05$), with SO_2 having the strongest association with the covariables, and PM_{10} having the weakest linear spatial relationship with traffic, and NO_2 weakly associated with the NPI industrial pollutants (Table 2.3).

Table 2.3. Statistical associations between traffic density, NPI industrial pollutants, and air pollutants, with the partial eta-squared value (η_p^2) indicating the proportion of the total spatial variation in the concentrations of the pollutants explained by each covariable.

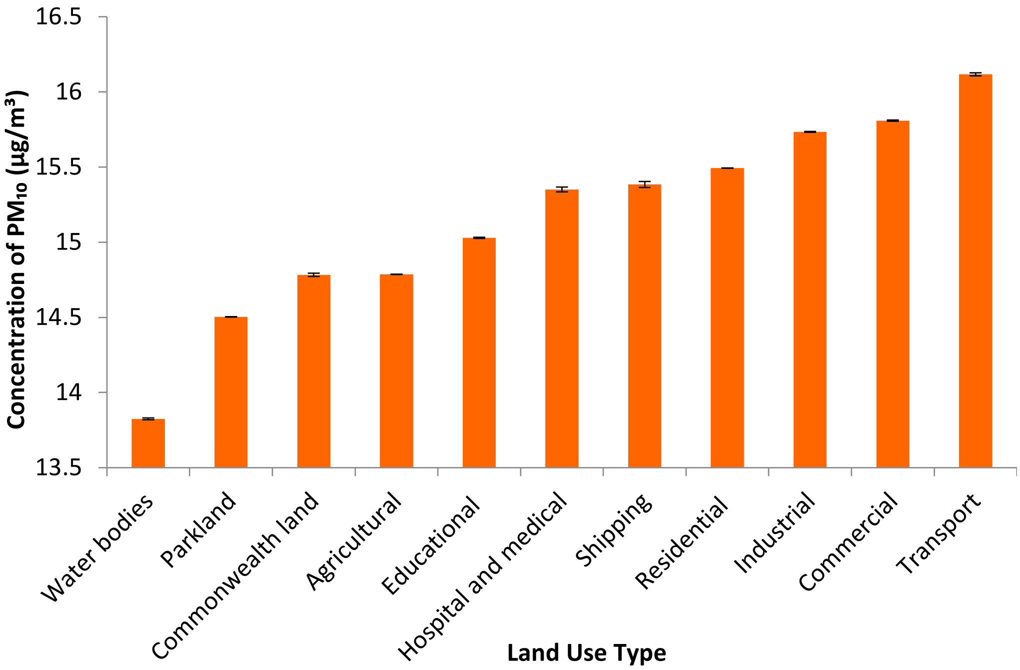
Air Pollutant	Partial eta square (η_p^2)		P value	
	Traffic Density	NPI Pollutants	Traffic Density	NPI Pollutants
PM_{10}	0.374	0.123	0.000	0.000
NO_2	0.375	0.057	0.000	0.000
SO_2	0.529	0.182	0.000	0.000

ANCOVAs with Bonferroni's *post hoc* tests were used to test for differences in air pollutant concentrations amongst the different land use types (Figures 2.4-2.6), after controlling for the effects of source, in the form of traffic and

NPI industrial pollution. The residual variation in the data (Estimated Marginal Means; EMMs) was used as a dependent data variable and analysed univariately to test the potential effect of land cover type on ambient air pollutant concentrations (Figures 2.4-2.6).

The general trend in the exploratory model indicated a significant association between vegetation and lower air pollutant concentrations, with parklands being associated with lower concentrations for all air pollutants except SO_2 (Figure 2.4 and Figure 2.5). PM_{10} and NO_2 shared similar concentration patterns, as their lowest concentrations occurred in areas categorised as water bodies and parklands (Figures 2.4 and 2.5), while shipping land use was associated with the lowest SO_2 levels (Figure 2.6).

Areas categorised as commercial, transport, and industrial land use demonstrated high concentrations for all pollutants. PM_{10} had the highest concentrations in transport related areas and NO_2 in shipping related areas (Figure 2.4 and Figure 2.5). SO_2 displayed a different pattern, with the highest concentrations being associated with agricultural land (Figure 2.6).



925

926 **Figure 2.4.** PM_{10} concentrations for areas with a land use type designation.
927 Data is displayed as estimated marginal means (± SEM).

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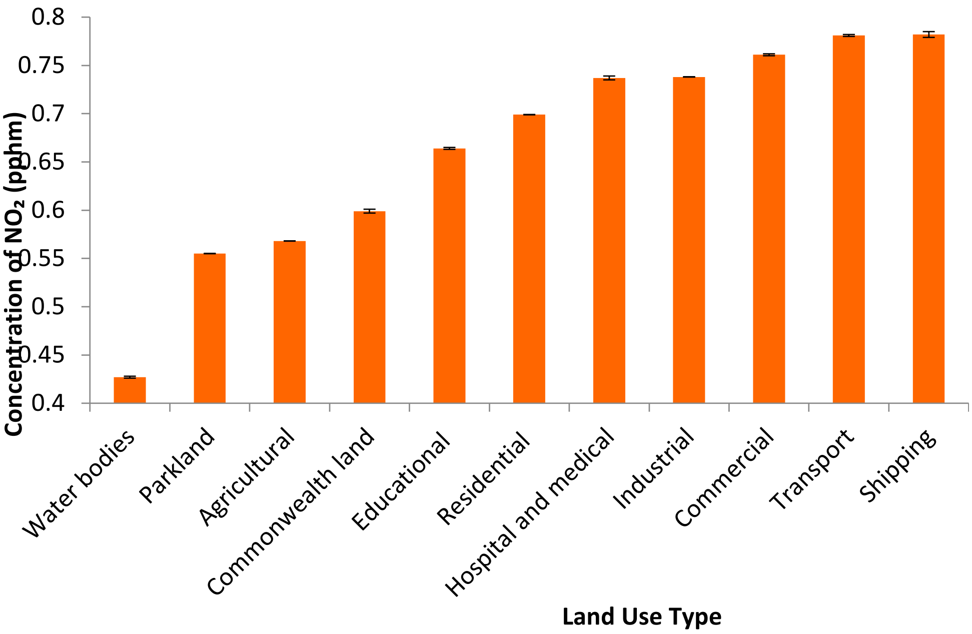

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930 **Figure 2.5.** Ambient NO_2 concentrations for areas with a land use type
931 designation. Data is displayed as estimated marginal means (± SEM).

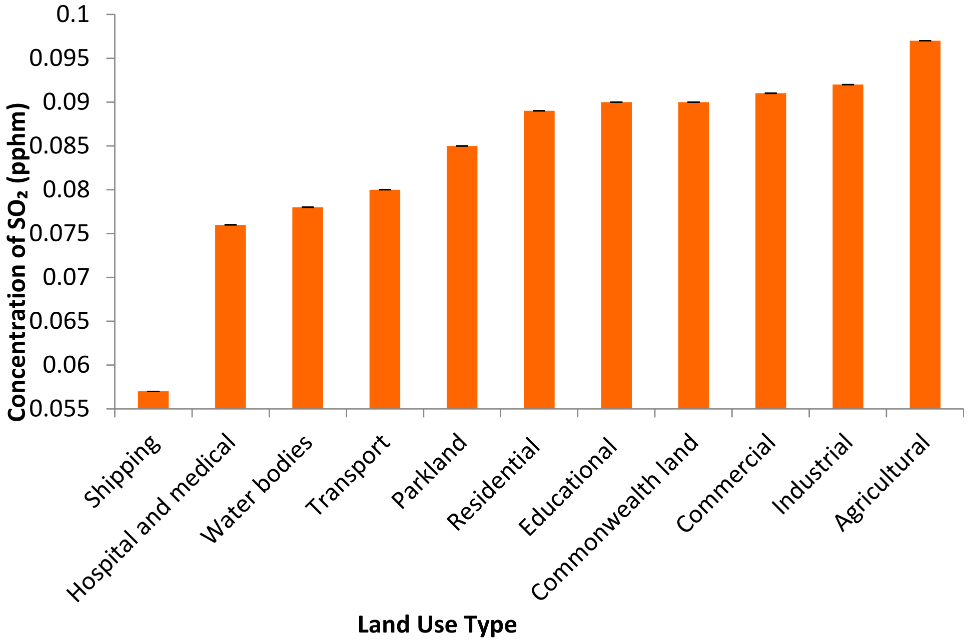

Figure 2.6. Ambient SO_2 concentrations for areas with a land use type designation. Data is displayed as estimated marginal means (± SEM).

2. The effects of different urban forestry types on air pollutant concentrations

The associations between the air pollutants and covariables, traffic density and NPI pollutants are shown in Table 2.4. All associations were statistically significant ($p < 0.05$), with each air pollutant following a similar trend to the previous exploratory model. Associations between air pollutant concentrations and proximity to source were indicated by the partial eta-squared values, with SO_2 having the strongest association with both covariables and PM_{10} having the weakest linear spatial relationship with traffic, and NO_2 weakly associated with the NPI industrial pollutants (Table 2.4).

Table 2.4. The covariables of traffic density and NPI industrial pollutants, their p values, and their partial eta squared (η_p^2) associations with each air

pollutant for the vegetation model with the η_p^2 indicating the proportion of the total variation attributed to each covariable for each pollutant.

Air Pollutant	**Partial eta square (η_p^2)**		**P-value**	
	Traffic Density	**NPI Pollutants**	**Traffic Density**	**NPI Pollutants**
PM_{10}	0.341	0.103	0.000	0.000
NO_2	0.360	0.045	0.000	0.000
SO_2	0.521	0.169	0.000	0.000

ANCOVAs with Bonferroni's *post hoc* tests were used to test for differences in air pollutant concentrations amongst areas with the different vegetation types, and the subsequent EMMs were analysed univariately to test the potential associations between vegetation type on ambient air pollutant concentrations (Figures 2.7-2.9).

SO_2 and PM_{10} air pollutants demonstrated lower concentration EMMs for areas covered by broadleaf evergreen forest and mangroves, except for NO_2 which only demonstrated low concentrations for broadleaf evergreen forests (Figures 2.7-2.9). The higher concentrations for SO_2 and PM_{10} were found in either shrubland or croplands, except for NO_2 which exhibited its highest concentrations in mangrove areas (Figure 2.8) and SO_2 with areas with sparse vegetation (Figure 2.9).

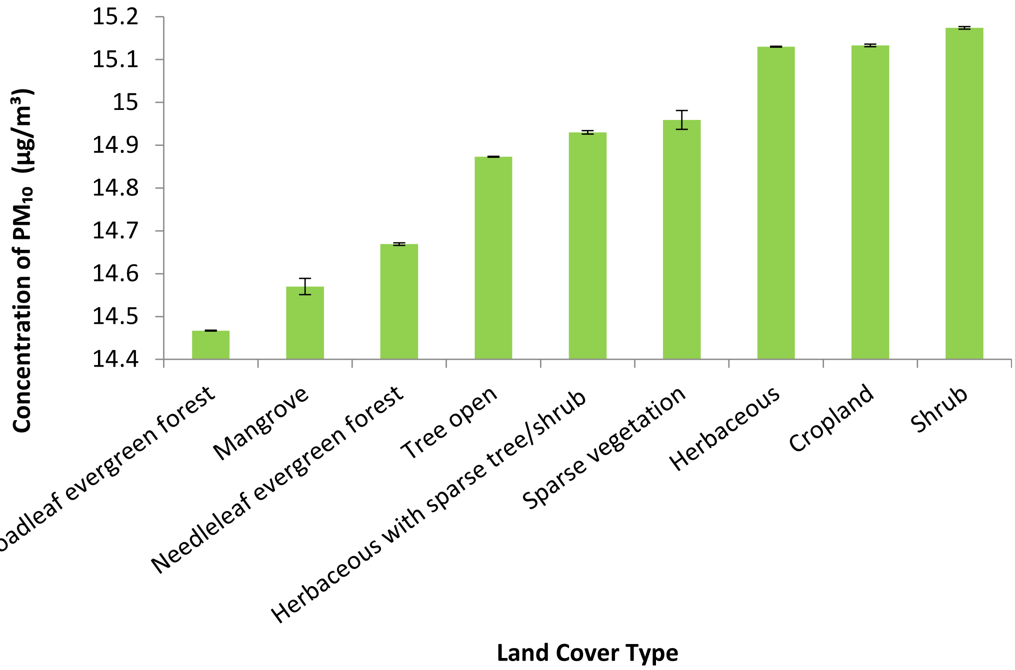

Figure 2.7. Ambient PM_{10} concentrations for areas with vegetation type designation. Data is displayed as estimated marginal means (± SEM).

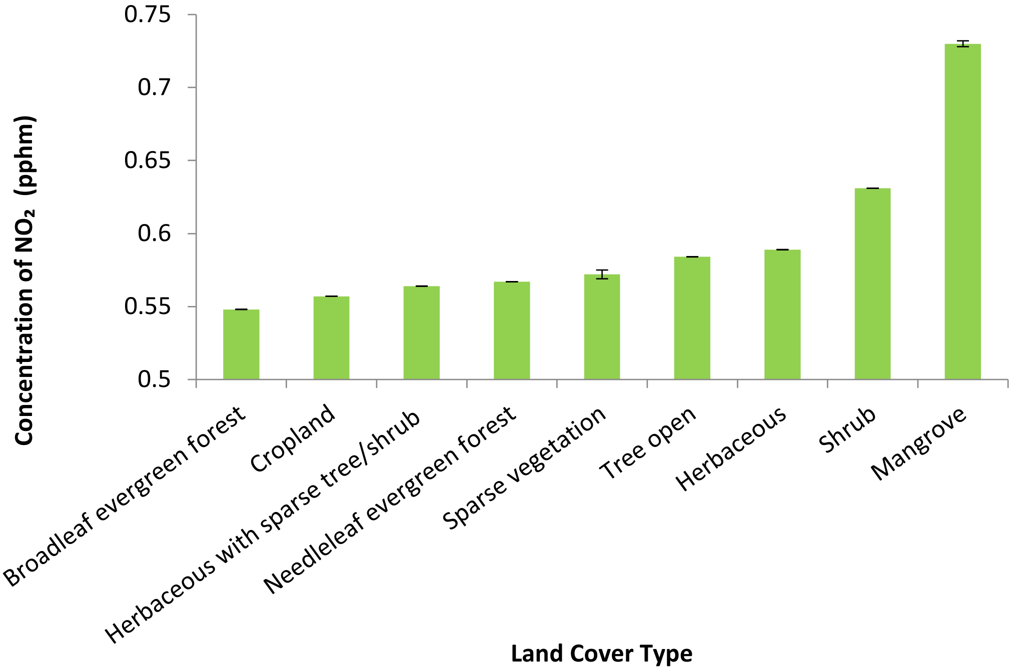

Figure 2.8. Ambient NO_2 concentrations for areas with vegetation type designation. Data is displayed as estimated marginal means (± SEM).

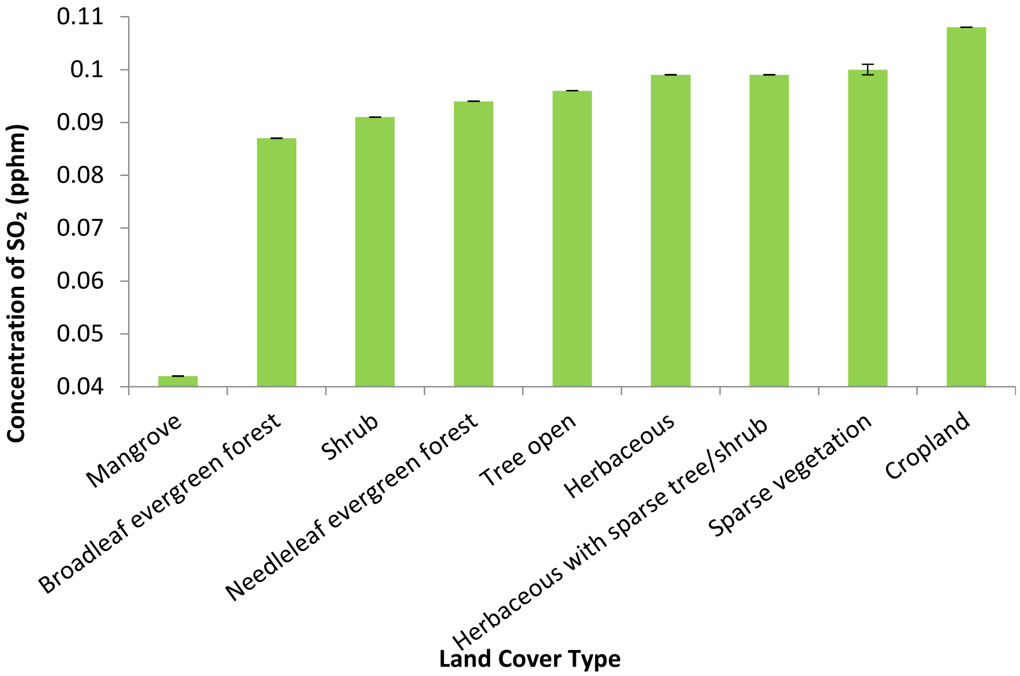

Figure 2.9. Ambient SO_2 concentrations for areas with vegetation type designation. Data is displayed as estimated marginal means (± SEM).

Discussion

1. General overview

The current research has investigated the relationship between source corrected air pollutant concentrations and urban areas, with particularly high levels detected in areas with anthropocentric based land uses coupled with a lack of vegetation. The correction for anthropogenic sources ensured the spatial relationships between land use or vegetation type and air pollutants were explicitly tested. Consequently, the associations between land uses such as transport, commercial, and industrial related activities, and high level of ambient air pollution were confirmed. Contrastingly, the significant association detected between parklands and low pollutant concentration demonstrated the impact of vegetation and its ability to influence air pollutant concentrations in an urban environment.

Although urban forestry has generally been associated with improved air quality [45, 88-90], few studies have investigated the potential of different vegetation types on an entire city scale with air pollution mitigation. The current research found different types of vegetation influenced air pollutants differently with broadleaf evergreen forests generally tending to be associated with lower air pollutant concentrations. While this study did not manipulatively appraise the causality of the relationship between urban forestry and air pollution, the associated findings align with existing findings, providing further support that such a causal pattern may exist.

2. The inclusion of NPI industrial concentrations and traffic data

Traffic density and industrial pollution were added as covariables to correct for pollutant source and ensure the main effects of land use and vegetation type were investigated in this study. The influence of these were elucidated as all pollutants were positively and significantly associated with the covariables across both exploratory models with SO_2 having the strongest association with both, and PM_{10} having the weakest with traffic and NO_2 with the NPI industrial pollutants. Interestingly, the weak association between PM and traffic density was in contrast to other published literature as increased incomplete combustion tends to occur in traffic dense areas or during periods of heavy traffic congestion [91-93]. This difference in findings may be driven by traffic conditions being strongly related to the diurnal peak hour patterns, in which case the use of annual averages in these exploratory models may have had insufficient temporal resolution to detect these associations [94, 95]. The significant pollutant associations with the NPI industrial concentrations were novel in their own right, as NPI industrial data had not been frequently incorporated into exploratory models such as those presented here, and they confirmed the impact of industrial pollution point sources on ambient air quality. The significantly strong association with SO_2 is possibly driven by the types of industries represented in this dataset which includes a wide range of industrial processing and manufacturing facilities [72]. Consequently, these findings also highlighted the potential for incorporation of these kind of datasets into future research.

3. The associations between different urban land uses and air pollutant concentrations

Areas categorised as commercial, transport, and industrial land use demonstrated high concentrations for all pollutants while parklands were associated with lower concentrations PM_{10} and NO_2 and shipping was associated with the low SO_2 concentrations. Parklands were associated with lower PM_{10} concentrations in the current study, and effect that has previously been observed in other air pollution models, with urban forestry negatively contributing to PM in models from Finland, Denmark, United Kingdom, Germany, Austria, Hungary, Switzerland, Italy, and Spain [96]. The main vegetation based mechanism associated with reduced PM levels is deposition. This occurs when suspended particulate matter is deposited onto the surface of a plant through impaction, interception, settling, or diffusion [97]. A plant's morphological characteristics could increase its particulate capture, with hairy or rough bark or leaves, complex structures, larger surface areas, and waxy epicuticular layers associated with increased PM deposition [98, 99]. Similarly, the low NO_2 concentrations across parklands was also been due to the mitigating effects of vegetation. A previous study from Sydney found that air pollution was negatively correlated with tree canopy cover, and found a statistically significant spatial relationship between urban forestry and air pollution [45]. Jayasooriya *et al.* [100] modelled air pollution removal by urban forestry in an industrial precinct in Victoria, Australia, and found that urban forestry had the potential to remove NO_2, SO_2, and PM_{10}. The value of urban forestry in Sydney was also outlined by Lin *et al.* [59], who found it had the potential to provide a wide range of ecosystem benefits, including air pollutant removal. Brack [101] assessed the ecosystem services of trees in Canberra, Australia, and found that the contribution of urban trees to the reduction of energy consumption, amelioration of air pollution and the improvement to local hydrology had an estimated annual value of $20–67 million USD [101].

These trends are not exclusive to Australia, with cities globally experiencing similar outcomes when urban forestry is increased, despite the differences in climate, location and anthropogenic influences [58, 88, 99, 102]. A study from Taipei, Taiwan found that both natural and semi-natural urban green spaces had negative relationships with NO_x and NO_2 [103]. This relationship was confirmed by Klingberg *et al.* [89], who found vegetated sites across Gothenburg, Sweden had lower NO_2 concentrations than non-vegetated sites. While Cohen *et al.* [104] found urban parks across Israel were associated with lower concentrations of NO_x and PM_{10}, when compared with urban street canyons.

A spatially dependent mechanism for lower NO_2 concentrations due to dilution effects from the presence of parklands and urban forests is possible [81, 88, 89, 105]. Dilution occurs through an increase in the distance between the source of pollution and the point of sampling. Urban parklands and forestry are beneficial for anthropogenic pollutant dilution as they increase the distance from pollutant source without increasing anthropogenic pollutant concentrations [81, 88, 89]. Vegetated areas also provide a cleaner air source during photosynthetically active periods due to oxygen emission, thus further reducing the concentration of pollutants through atmospheric mixing [88, 89]. The association between water bodies and lower PM_{10} may have been due to multiple factors. The majority of the water bodies are proximal to parklands (Figure 2.2), which may have led to a spatial confound in the detected pattern. Additionally, simulations of cities with no urban water bodies have demonstrated increased wind speeds, which could allow particulate matter to remain suspended in the air column [106], while urban areas with natural or artificial water bodies may experience decreased wind speeds [106], facilitating particle deposition [88, 107, 108].

Anthropogenic SO_2 emissions are largely related to the combustion of sulphur rich coal and other fossil fuels, which are used in a wide range of sectors, including residential heating and cooking, industrial processing and manufacturing, electricity generation and shipping [78, 109-111]. However, in the current study, the highest SO_2 concentrations were associated with agriculture, followed by industrial and commercial land uses. The association between low SO_2 concentrations and shipping, seen in this current study, could have been driven by the growing use of low emissions fuels necessitated by global demand for the reduction in shipping related pollutants [112-115]. Furthermore, efficient dispersion of SO_2 along Sydney's coast, where the majority of shipping facilities are located, would have also influenced its concentration [116-118]. Additionally, shipping facilities are not a main source of pollution, but the vessels themselves [112, 117]. The relatively low output of shipping exhaust and the effect of the proximal water bodies and wind effects are likely reasons for the observed low pollutant levels in these areas.

High NO_2 concentrations in the current model were associated with transportation, commercial, and shipping land uses. This relationship is driven by petrol and diesel engines, which account for over 80% of NO_x emissions, with NO_2 being the most prevalent form of atmospheric NO_x [73, 119]. Additionally, the combustion of fossil fuels and industrial processes associated with diverse commercial activities and production are strongly correlated with NO_2 [58, 89, 120]. The current findings support previous studies conducted across Australia [56, 58, 66, 68, 121], Western Turkey [122], Thailand [123], and Canada [124].

The high concentrations of SO_2 in agricultural areas was unexpected; although the current observations align with an emerging understanding of the relationship between SO_2 and agricultural activities [125-128]. SO_2 can have impacts on human and animal health along with the surrounding environment [126-128]. Human and animal health impacts are especially prevalent in livestock houses that collect animal waste in manure pits underneath slatted floors above which the animals reside [126]. While the exact mechanisms and behaviour of this relationship requires further research, SO_2 is believed to be released from primarily organic wastes, animal manure, wastewater and the disruption of acid sulphate soils during agricultural activities [125-128]. Additionally, the release of SO_2 is the main precursor to acid rain which can contribute to the acidification of soils, lakes and streams [126-128].

4. The association between different urban forestry types and air pollutant concentrations

Air pollutants SO_2 and PM_{10} demonstrated lower concentrations in areas covered by broadleaf evergreen forest and mangroves while NO_2 only demonstrated low concentrations for broadleaf evergreen forests. The higher concentrations for SO_2 and PM_{10} were found in croplands while NO_2 exhibited high concentrations in mangrove areas. In the current study, PM_{10} concentrations were high in areas of shrub and croplands. These vegetation types were clustered at the western side of the study area, which is considered semi-arid and drought-prone, which may have driven this association [129]. Sydney experienced a prolonged and widespread drought from 2000 –2009 [64, 129], which would have contributed to increased levels of atmospheric PM_{10} from wind-blown dust [64].

Broadleaf evergreen forests and needleleaf evergreen forests were associated with lower ambient PM_{10} concentrations which aligns with the findings from previous research [51, 97, 105, 130-132]. The leaf and plant characteristics present across both broadleaf and needleleaf evergreen species such as hairy plant surfaces, waxy epicuticular layers, complex plant structures, larger surfaces areas and increased and prolonged vegetation/canopy density throughout the year are all known to enhance PM accumulation [51, 90, 97, 105, 131, 133].

Mangroves also had a noticeable association with low air pollutant concentrations for PM_{10} in the current study. Such effects have not been detected previously. Mangroves are coastal forests found in sheltered estuaries and along river banks and lagoons [134, 135]. There are several potential explanations for the observed air pollution remediation effect. Similar to the broadleaf and needleleaf evergreen forests, mangrove canopy cover is usually dense, with more than 70% cover, the leaves are waxy, and the plants possess complex and woody structures, thus potentially assisting with deposition of particulates [90, 120, 131, 132, 134, 135]. Additionally, the majority of Sydney mangroves were surrounded by broadleaf evergreen forests (Figure 2.3). These proximal vegetation types may have led to general area effects where air pollutants were removed by a range of independent mechanisms.

The association between low concentrations of NO_2 and broadleaf evergreen forests in this study supports the findings of Leung *et al.* [90] and Currie and Bass [136], who found leaf longevity and continuous photosynthetic performance throughout the seasons enables greater gaseous pollutant sequestration in this vegetation type. Gaseous pollutant uptake is dependent on stomatal conductance and photosynthetic capacity. Stomatal conductance is in turn dependent on leaf properties such as leaf area and orientation, while photosynthetic capacity is dependent on the leaf type and formation [137, 138]. Both of these favourable traits are prevalent in broadleaf evergreen forests [137-139].

The association between croplands and high SO_2 concentrations aligned with the previously discussed association between SO_2 and agriculture, and with previous research [125-128, 140]. While lower SO_2 concentrations were detected in areas with mangroves and broadleaf evergreen forests. The mechanisms behind these effects are likely similar to those proposed for NO_2 previously. Interestingly, the favourable traits for gaseous pollutant mitigation in broadleaf evergreen forests are also present in mangroves, which could explain the association with low SO_2 concentrations in the current study. Most mangrove trees are evergreen with sclerophyllous leaves that have an average leaf life span of 16 months, similar to other terrestrial evergreen species [141, 142]. Additionally, the proximity to broadleaf evergreen forest may have combined to lead to general area effects.

Conversely, mangroves had a noticeable association with high concentrations of NO_2 in the current study. Mangroves in their natural state act as a sink for nitrogen [143, 144]. However, modification of their biochemical processes due to anthropogenic nutrification and denitrification, along with increased nitrogen loading, may alter these processes resulting in mangroves acting as sources of atmospheric nitrogen [143-145]. Further, all of the mangrove sites within the current study could have been influenced by anthropogenic effects due to proximity to urban areas, potentially influencing the detected association with NO_2.

Conclusions

The present research is the first to provide such an insight into the associations between vegetation and air pollution in order to quantify and evaluate the spatial variation of air pollutant concentrations associated with different forms of urban forestry. The incorporation of anthropogenic pollutant sources ensured that the hypothesis that urban forestry was associated with air pollution removal was explicitly tested. Relationships between different vegetation types and air pollutant concentrations were established, with broadleaf evergreen forests consistently associated with lower pollutant concentrations. Areas classified as parklands and water bodies displayed consistently lower air pollution concentrations, confirming the negative association between urban forestry and ambient air pollution concentrations on a city-wide scale. The statistically significant relationship between urban forestry and low air pollutant concentrations promotes the value of urban forestry, while the vegetation insights may assist with species and conservation area selection to ensure targeted vegetation applications provide the greatest air quality benefits.

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3. The Determination Of Sound Absorption Coefficients Of Green Walls And Species

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Vertical greening systems, noise pollution, indoor environment, green buildings, nature based solutions, sustainability.

Abstract

The increasingly clustered nature of urbanised areas and competing requirements of modern day life has made our daily lives noisier as individuals are exposed to significant levels of noise pollution. Noise pollution is now considered a pollutant of concern as detrimental noise related health impacts increase. Various methods and materials are employed in urban settings to mitigate noise, yet solutions are often inadequate. However, a growing body of research indicates that vegetation could effectively reduce noise, but this field of research is limited. Thus, this research aimed to assess the effectiveness of planted green modules for noise pollution mitigation through sound absorption.

This was determined by testing the sound absorption coefficient of the green wall modules and the different plant species using a reverberation chamber in accordance with Australian Standard methodology AS ISO 354–2006 “Acoustics: Measurement of sound absorption in a reverberation room.” Our findings revealed the sound absorption coefficients of our planted green modules exceeded 0.5 for most frequencies, with one plant species reaching more than 0.9. Comparatively, our planted green modules outperformed commonly used building materials and other vertical green systems, typically achieving a maximum sound absorption coefficient of 0.6 or less. These findings underscore the potential of vegetated green walls to play a significant role in mitigating the effects of noise pollution while offering numerous positive impacts on our urban environments and their occupants.

Introduction

After decades of rapid urbanisation, industrialisation and population growth, the scarcity of land has resulted in dense urban mosaics. The result is residential and commercial buildings constructed in very close proximity to transport frameworks, such as highways, airports, shipping terminals, railways, and industrial and manufacturing sites, exposing occupants to significant levels of noise pollution [146]. Consequently, our cities are becoming louder and environmental noise pollution has been established as a universal urban stressor with increasingly negative impacts on human health [147-149]. The World Health Organisation considers noise pollution to be the third most detrimental type of pollution in urban metropolises, with conservative estimates predicting at least one million healthy years of life are lost annually due to traffic-related noise across the European Union and Western Europe [150, 151]. Exposure to noise pollution can impact human health in a multitude of ways, including hearing loss, breathing difficulties, blood pressure increases, circulatory disorders, sleep disturbances, ulcers, asthma, anxiety, depression, behavioural disorders, difficulty concentrating, gastrointestinal issues, while also causing psychological annoyance [146, 151].

These external environmental changes to the urban environment are also being mirrored internally. Internally, our professional landscape is changing as open plan offices are increasing, and the work from home dynamic and availability is now the new way of working since the pandemic, despite aspects that can both hinder and promote productivity [152-154]. These internal and external changes can have a cumulative effect on noise pollution, subsequently impacting productivity, workplace satisfaction, quality of life, and overall health. While studies have investigated and elucidated the impact of noise pollution on job performance, productivity, and work satisfaction, less has been done to investigate how to reduce it [152, 155].

At present, there is a range of different methods and materials utilised in the urban environment for noise mitigation, with the predominant solution being specially constructed noise barriers to protect citizens from the source [11, 12]. Other noise reduction strategies focused on reducing the source of noise pollution through the implementation of quieter engines and new road surfaces [13]. However, these solutions are often insufficient, as it is estimated that up to 44% of residents are subjected to noise levels above the recommended limits for health [14-16]. Consequently, the search for viable alternatives has recently shifted, with vegetated solutions such as green walls gaining in popularity [149, 156]. Currently, a small but growing body of evidence suggests that vegetation can also provide effective noise reduction benefits [156-159]. However, few studies have investigated the noise mitigation properties of green technologies, as opposed to the presence of simple vegetation, despite their potential to improve the acoustic environments of a community affected by noise pollution. Thus, this research aimed to investigate the effectiveness of vegetated green wall modules for noise pollution mitigation through sound absorption.

Method

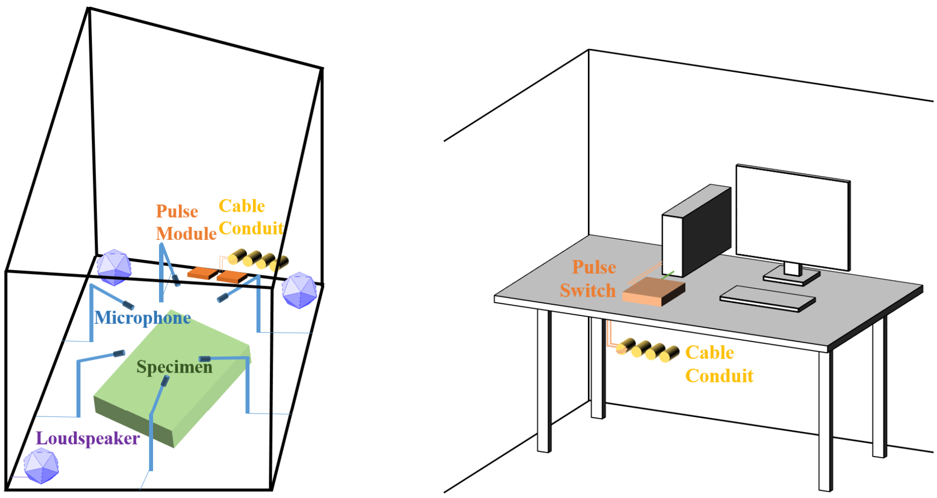
To determine the sound absorption coefficient of the green wall modules and the different plant species, a series of tests were carried out using the reverberation room of Tech Lab, Faculty of Engineering and Information Technology, University of Technology Sydney (UTS; Figure 3.1). Testing was carried out in accordance with AS ISO 354–2006 “Acoustics: Measurement of sound absorption in a reverberation room.” The weighted sound absorption coefficient α_w was determined using the standard AS ISO 11654-2002 “Acoustics: Rating of sound absorption – Materials and systems”, and the NRC (Noise Reduction Coefficient) was determined per ASTM C423-90A. The empty room reverberation time was measured with the sample and frame removed from the reverberation room.

1. Description and Testing

The determination of the sound absorption coefficient required a large test sample area between 10 and 12 m^2. This was achieved using 42 green wall modules with an area of 3.48 m long and 2.97 m wide (total area is 10.34 m^2), meeting the test sample area requirements of the ISO 354 standard. The ratio of width to length of 0.85 also met the standard requirements.

The soil moisture and temperature before the sound absorption tests were respectively 0.154~0.297 m^3/m^3 and 22.4~22.8°C. After several runs of the sound absorption test, they were respectively 120~336 m^3/m^3 and 23.0~23.2°C. They were measured from randomly selected samples amongst the test modules using the PROCHECK-11 with a TEROS-11 sensor. The frequency range of interest, i.e. 100-5000 Hz, was measured under the same test conditions in the reverberation room (Figure 3.1), with the measurements taken in 18 one-third-octave bands in that range.

Five green wall module samples (soil-filled module, empty module, and planted modules with three different species) were tested, each under three different sample mounting conditions. The three planted module tests were carried out with green wall modules that were planted with a single species. This was to ensure the reverberation and sound absorption of the individual species were tested, and those three species were *Philodendron* (Hope) *selloum*, *Nematanthus glabra*, and *Nephrolepis exaltata* (Boston Fern). These species were chosen as they are commonly used in green infrastructure across indoor and outdoor environments.



(a) Test Room (b) Control Room

Figure 3.1 - Diagrams of the test system for sound absorption measurements at UTS (a) measurement setup in the reverberation room and (b) the measurement system in the control room

2. *Mounting and Position of Sample in the Reverberation Room*

The green wall modules were installed on the floor of the reverberation room to comply with the requirements of ISO 354 Appendix B. Specifically, the test specimen was installed and tested under different combinations of the following mounting conditions:

- **Mounting Condition 1:** The screw holes at the corners of the upper surface of the individual modules were covered to simulate the actual application to a wall.
- **Mounting Condition 2:** The perimeter edge of the test sample area was sealed to prevent the edges from absorbing sound. This included sealing the junction between the perimeter edge and the reverberation room floor.
- **Mounting Condition 3:** The joints between the adjacent modules were covered to prevent the side edges of the individual modules from absorbing sound.

The mounting condition combinations for each sample included:

- No seal was applied
- Condition 1 was applied
- Condition 2 was applied
- Conditions 1 and 2 were applied
- Conditions 1, 2 and 3 were applied

The sample was installed to be a minimum of 1 m from any wall of the test room, and not parallel to the edge of the room as required by the ISO 354 standard. The position of the test specimen was within the region specified in Table 3.1 and Figure 3.2.

Table 3.1 – The positions of the test specimen in the reverberation room

Corner Ref. Number	X coordinate (m)	Y coordinate (m)
1	1.31	1.24

2	1.09	4.23
3	4.68	4.50
4	4.90	1.51

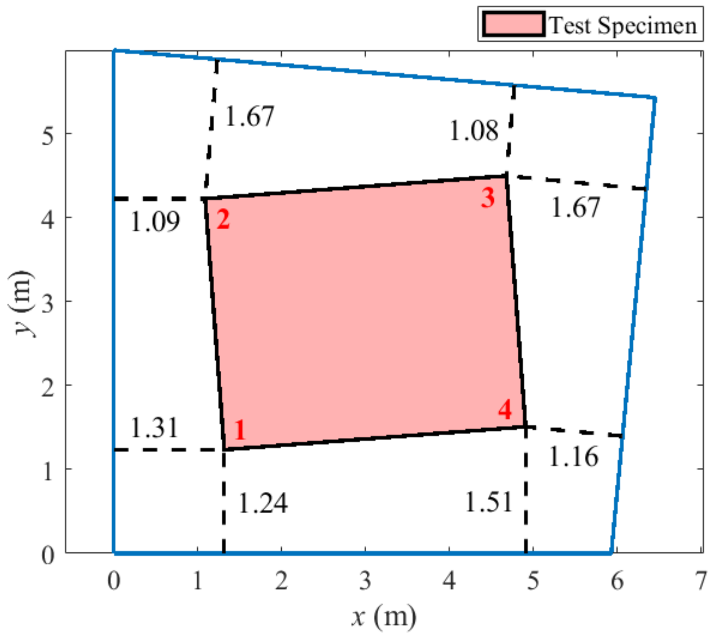


Figure 3.2 – The position of the test specimen (top view) and the distances, marked with numbers in meters, between the corners of the specimen and the walls of the reverberation room

Results And Discussion

During the measurements, the temperature and relative humidity in the empty room were 22°C and 50%. The temperature and relative humidity in the room during the treatment measurements ranged from 22°C and 23°C and 54% to 67%, respectively. Figure 3.3 highlights the reverberation time of the empty room and the planted modules across all three mounting conditions. After introducing the planted modules into the reverberation chamber, there was a significant decrease in the reverberation time, particularly in the frequency range between 125Hz and 1000Hz. In this study, the difference in the reverberation time in an empty room compared to a room with planted modules was approximately 6-7 seconds in that frequency range (Figure 3.3).

These planted modules also outperformed reverberation times of other published vertical greenery systems and building materials by approximately 2-4 seconds, subsequently highlighting their potential for noise pollution mitigation [156, 160, 161].

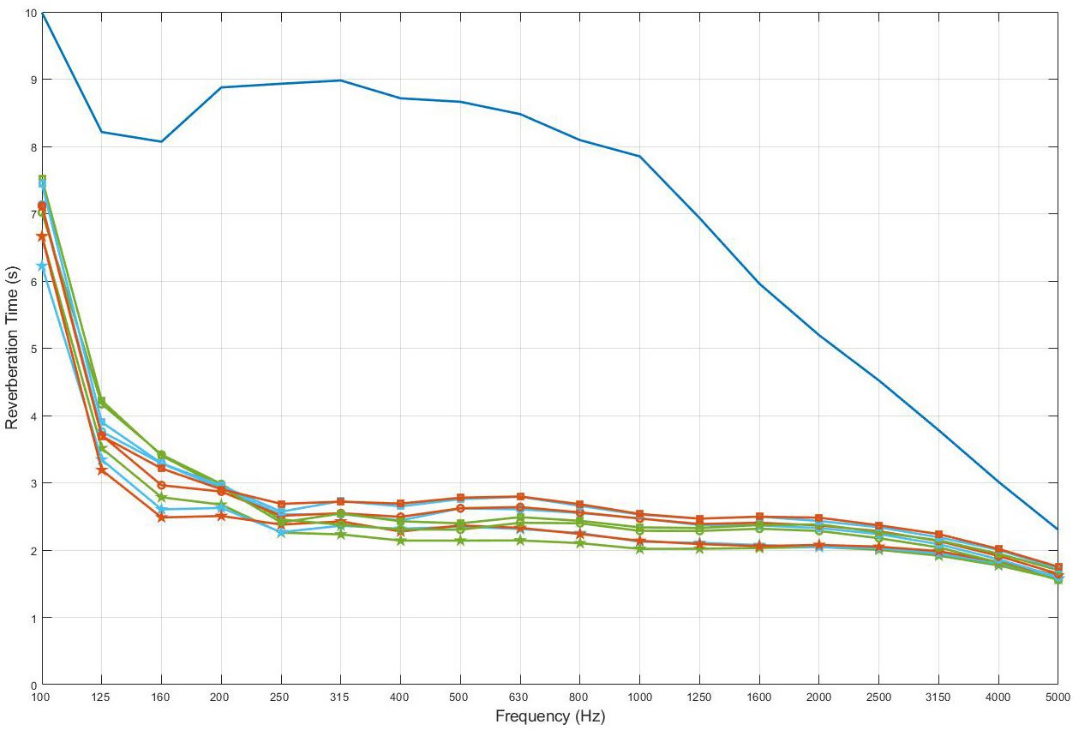


Figure 3.3 - The reverberation times of the three planted samples across the different mounting conditions and the empty room (dark blue solid line). The plant species were represented using different markers (*Philodendron* is the star, *Nematanthus* is the circle, and *Nephrolepis* is the square), and the mounting conditions as colours (green is mounting condition 1, blue is mounting condition 2, and orange is mounting condition 3).

The curve of the weighted sound absorption coefficients over frequencies is shown in Figure 3.4. The results demonstrated the sound absorption coefficients of our vegetated modules were above 0.5 for most frequencies, peaking at more than 0.9 for one of our plant species. *Nematanthus glabra* performed better compared to the two other plant species with higher sound absorption coefficients across a range of frequencies. Furthermore, the tested planted modules in this research consistently outperformed other vertical green systems in the published literature, which tended to achieve maximum sound absorption coefficients of approximately 0.65 or less [Figure 3.5, [156, 160]. Interestingly, these differences could be due to substrate or plant differences.

While the authors tried to compare similar methods and research, the differences in substrate type and mixtures, moisture content, and leaf area density could influence absorption [160, 162, 163]. In other studies, the different substrates tended to perform well at lower frequencies, while the plants themselves performed better at higher frequencies by absorbing the acoustic energy [160, 162, 163]. This could highlight the importance of considering both the plant and soil system when selecting green wall properties to address noise pollution. However, in this current study, the sound absorption coefficients remained consistently high across an extensive range of frequencies and outperformed other vertical greenery systems, suggesting the current module structure, soil mixture, and plant selection could be very effective when implemented for noise pollution mitigation.

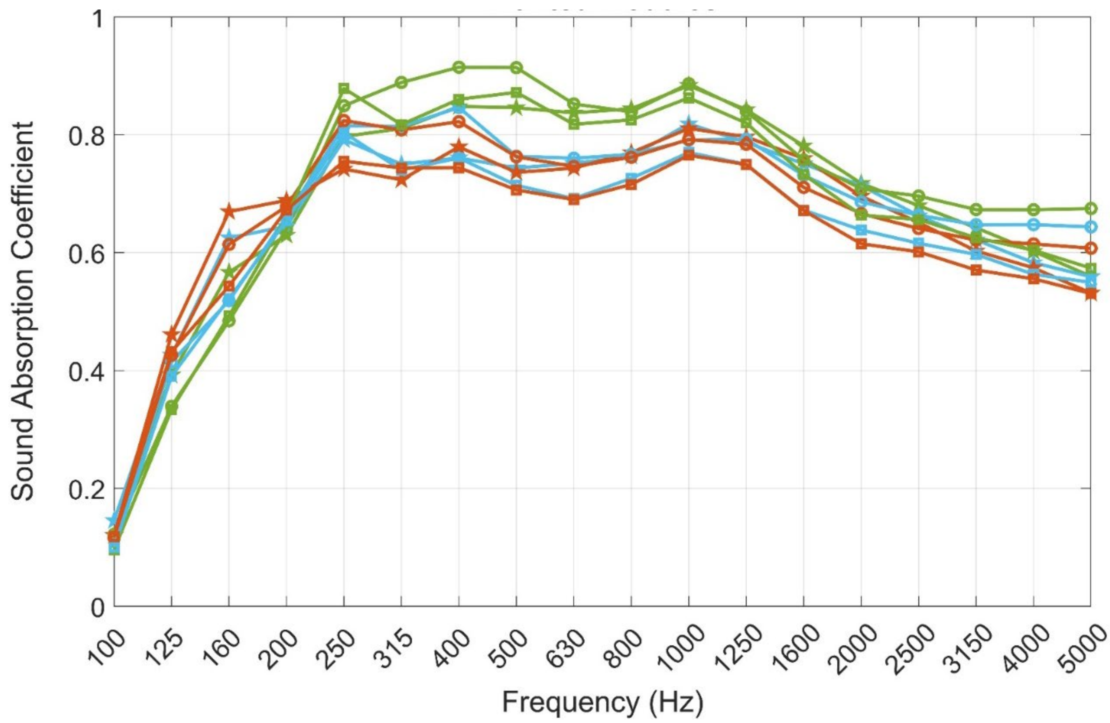


Figure 3.4 - The sound absorption coefficients for the three plant species across the three mounting test conditions were represented using different markers (*Philodendron* is the star, *Nematanthus* is the circle and *Nephrolepis* is the square), and the mounting conditions as colours (green is mounting condition 1, blue is mounting condition 2 and orange is mounting condition 3).

When compared to other building materials, the planted modules outperformed almost every other building material across all frequencies, with the exception of fibreglass in the higher frequencies [Figure 3.5,[156, 160]. The significance of these results demonstrated that the tested planted modules and other vertical greening systems outperformed conventional building materials often used for noise pollution mitigation and highlighted their potential as an important part in mitigating the impact of noise pollution on the urban environment. The significance of these results was further supported by the frequencies where the planted module coefficients were considerably high, as they were frequencies often experienced in the urban environment, suggesting that a targeted application of vertical greening systems could vastly reduce noise pollution and improve people's quality of life [156, 160].

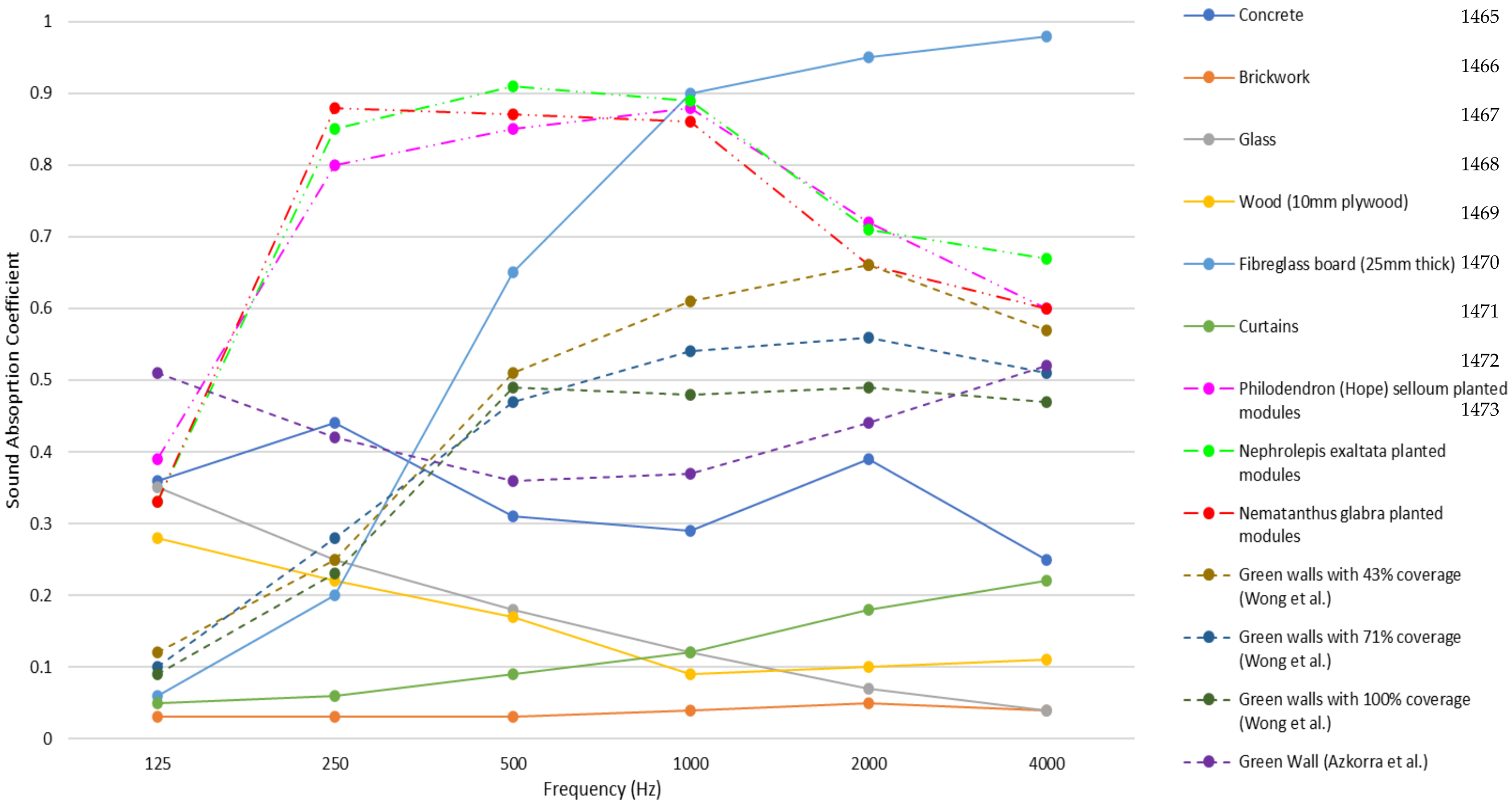


Figure 3.5 - Sound absorption coefficients comparing common building materials (solid lines), other published green wall (dotted lines) and current research (line and dotted lines) [156, 160].

Conclusions

As noise pollution is becoming an increasing problem in the urban environment, we need to look elsewhere to address the issue at hand as current solutions, materials and methods we have in place may not be enough. Thus, this current research recognized the lack of studies associated with applied greenery as a noise pollution solution and aimed at addressing that by investigating the effective of planted modules for noise pollution mitigation through sound absorption. These results highlighted the potential for vegetated green walls to play an important part in mitigating the impact of noise pollution, as our planted module consistently outperformed commonly used building materials and other green walls published in the literature. Furthermore, these findings not only highlighted the acoustic benefits of vertical greening systems but are also additive to the justification of green wall implementation in the urban environment. Unlike other building materials and urban planning approaches, vertical greening systems reduce noise pollution through the presence of the vertical structure itself, the soil mixture, and the vegetation while having other positive impacts simultaneously. Some of these positive impacts include the reduction of the urban heat island effect, improved thermal comfort through evapotranspiration and improved protection from solar radiation. The presence of vegetation filters and reduces air pollution through deposition, sequestration, and biodegradation and a person’s productivity, wellbeing and quality of life can be improved when in the presence of vegetation.

Despite the numerous benefits of vertical greening systems already documented, more research is required regarding their potential to reduce noise pollution. To further advance this research, controlled acoustic studies are needed in combination with full scale, uncontrolled in-situ investigations. The former should assess the impact of different variables of a vertical greening system, such as plant selection and density, soil composition and depth, and system configuration. The latter should be undertaken to gain insight into their acoustic impact, as controlled experiments do not reflect the realities of an urban soundscape or the dynamic environmental conditions. Ultimately, while more research is required, this should not be used as a barrier to implementation, given the cumulative benefits of vertical greening systems for noise pollution and beyond.

Acknowledgements

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4. The Need For Multifaceted Approaches When Dealing With The Differing Impacts Of Natural Disasters And Anthropocentric Events On Air Quality

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Keywords

Coronavirus, Bushfires, Air Pollution, Policy Impacts, Management Strategies

Abstract

Air pollution associated health issues are increasing globally. This is due to both anthropogenic sources, such as traffic, and natural sources, such as bushfires. Natural disasters, such as bushfires, impact air quality by releasing large concentrations of pollutants affecting respiratory health. However, another recent global event has also had severe impacts on the environment and health, the global COVID-19 pandemic. Global pandemics, such as COVID-19, can also influence air quality by altering human activity, resulting in its own associated health impacts. This study aimed to investigate the impact of a natural disaster and global pandemic on outdoor ambient air pollution by quantifying and comparing the spatial distribution of two air pollutants, nitrogen dioxide (NO_2) and particulate matter (PM_{10}), during the different periods across the Greater Sydney region, Australia, while correcting for anthropogenic sources and meteorological influences such as temperature and rain. COVID-19 and bushfire affected periods were

compared to a control period when both of these influences were absent. We found that NO_2 was significantly higher during the COVID-19 pandemic than during the control period and the recent 2019 bushfires. Conversely, PM_{10} was significantly lower during the COVID-19 pandemic than the bushfire and control periods. The spatial distribution of both pollutants and influencers also varied across the study site. These results suggest that both events markedly impacted air quality, although they impacted the air pollutants differently. These findings further demonstrate a greater need to understand the impact of natural disasters and anthropocentric events on air pollution as multifaceted, spatially relevant policies are required to address these events, particularly if they increase in frequency or severity in the future.

Introduction

Air pollution is increasing as emissions from anthropogenic sources, such as industry, transport, and agriculture, intensify [164]. Reduced air quality has negative health consequences, and air pollution poses one of the most substantial risks to human health [165]. It is estimated that ambient air pollution kills more than 8.8 million people annually [166, 167] and this figure is expected to increase as 90% of the global population are exposed to air quality standards below the WHO Air Quality Guidelines [166]. Studies have shown that exposure to air pollutants, such as particulate matter with a diameter of less than 10μm (PM_{10}) and gaseous pollutants such as nitrogen dioxide (NO_2), are associated with respiratory and cardiovascular mortality [167, 168].

Natural sources of air pollution, such as bushfires, also have the ability to increase air pollution concentrations [169]. Natural bushfire seasons in Australia tend to occur during Summer and are characterised by drought, minimal rainfall, high temperatures, dry vegetation and high fuel loads, low humidity, gusty or strong winds, and a natural source of ignition such as transported burning embers or lightning [170-172]. An example of this was the 2019–2020 ‘Black Summer’ Australian bushfire season, which was a period of abnormally severe bushfires throughout Australia, with New South Wales (NSW) being the worst affected state [173]. During these bushfires, Canberra and Sydney were considered to have the worst air quality of any city in the world [170, 174]. Many sporting events and festivals were cancelled in Canberra and Sydney due to public health concerns [174]. Canberra experienced levels of $PM_{2.5}$ pollution that were approximately 100 times the levels considered safe [170].

Simultaneously, Sydney experienced periods where air pollution was approximately 11 times greater than the levels deemed hazardous to human health, while experiencing hazardous levels of air pollution for at least 30 days during the bushfires [175]. These bushfires impacted air quality by releasing significant amounts of pollutants through the burning of vegetation, contributing an estimated 20% to NO_X emissions globally [169]. Horsley *et al.* (2019) found bushfire smoke was positively correlated to asthma hospitalisations, while outdoor urban air pollution of NO_2 and PM has also been associated with greater hospital admissions for asthma and heart disease [176]. Smoke from extreme bushfires has previously been proven to increase mortality rates [177], with the 2019-2020 bushfire event causing an estimated 3151 cardio-respiratory hospitalisations and 417 premature deaths in eastern Australia alone [178].

Months following the bushfires saw a significant decrease in anthropogenic activity due to the COVID-19 pandemic and associated lockdowns and travel restrictions. During March-May 2020, residents remained at home and in isolation unless necessary. Subsequently, there was a drastic decline in transport and other activities as restrictions were imposed by the Australian Government [179]. Literature published early in the pandemic suggested more lives were saved by reducing air pollution-related mortality than deaths from COVID-19 [180, 181]. Despite the global death toll from COVID-19 totalling over 650,000 at the time [182], the usual annual death toll associated with air pollution was 8.8 million [183-186]. Simultaneously, NSW's COVID-19 death toll was only 56 from the first case in January until December 31st 2020 [187], while premature deaths associated with air pollutants across Sydney have been estimated to be 643 – 1,446 annually [188].

Vehicular emissions, such as particulate matter of different sizes ($PM_{2.5}$ and PM_{10}), nitrogen oxides (NO_X) and sulfur dioxide (SO_2), normally contribute to 23% of air pollutants produced globally [177, 189]. Thus traffic-related or road-based variables are commonly incorporated in spatial studies of air pollution [190-194]. In particular, traffic count has been positively correlated with air pollutant concentrations, with Douglas *et al.* (2019) finding that traffic count was the strongest predictor for pollutant concentration variability for Sydney [191]. Kalisa *et al*. (2018) also found that both pollutants included in the current study increased in urban areas due to traffic congestion [195]. Furthermore, in Sydney, approximately 71% of total NO_X emissions are caused by vehicles, and peak concentrations of NO_2 occur near busy roads [65]. Hence, traffic metrics need to be included in air quality studies for Sydney to ensure differences in traffic during the different periods do not influence other effects.

Meteorological conditions also have an effect on air pollutant concentrations and their impacts. Elminir (2005) found NO_2 increased with temperature and Li *et al.* (2017) found extremely high temperatures significantly increased cardiovascular mortality caused by PM_{10} [167, 196]. Further, a recent study by Coker *et al.* (2020) examined the relationship between air pollution and COVID-19, and found a positive association between ambient $PM_{2.5}$ concentration and excess COVID-19 related mortality. Their study found a one $\mu g/m^3$ increase in $PM_{2.5}$ concentration was associated with a 9% increase in COVID-19 related mortality [197]. Additionally, a positive relationship between air pollution and COVID-19 mortality was detected in Mexico City that increased with age and was mainly driven by long-term pollution exposure [198].

Rainfall also has the potential to have significant effects on the concentrations of many atmospheric pollutants. Precipitation events can cause significant decreases in major air pollutants through wet scavenging and washout processes which remove the pollutants from the atmosphere [199]. For example, Kwak *et al.* (2017) revealed that PM_{10} concentrations decrease during rainfall, with the effect of rain washout being so great that it outweighs the increased traffic pollution from slower moving traffic during rain. Kwak *et al.* (2017) also found that the inverse of this washout relationship was true for NO_2, as the increase in traffic outweighed the washout effects by rain [200]. Thus, these were included as covariates in the current work to account for their potential influence on air quality and to correct for seasonal variance in meteorological effects.

This spatio-temporal study was conducted using a Geographic Information System (GIS) based method to ensure that variability in weather, traffic and air quality across Greater Sydney were accounted for. These methods have been found to be particularly useful when meteorological variables, such as rainfall or temperature, have high variability within a region [199] or across a city [201]. Additionally, the variability in traffic-related variables such as congestion, road length, and traffic density within an urban environment leads to variability in intra-urban air quality [202].

This study aimed to investigate the impact of a natural bushfire disaster and the COVID-19 pandemic on air pollution by quantifying and comparing the spatial distribution of two air pollutants, nitrogen dioxide (NO_2) and particulate matter (PM_{10}), during the different periods across the Greater Sydney region while correcting for anthropogenic and meteorological influences. This was achieved by interpolating daily concentrations of NO_2 and PM_{10} from the peak months of these events and a control month and statistically comparing them. The effects of traffic count, temperature, and rainfall, were accounted for to correct any potential confounds. It was hypothesised that there would be significantly higher concentrations of these pollutants during the bushfires than the COVID-19 period. The outcomes of this study builds on previous studies by furthering our understanding of the impacts of natural disasters and anthropocentric events on air pollution.

Materials And Methods

1. Study area

The area of interest for this study was the Greater Sydney region (Figure 4.1A). This was selected as it was the most frequently applied boundary for COVID-19 restrictions in NSW [203]. Additionally, Sydney is the most populated city in Australia with over 5 million people [176] with a higher population density, dwelling density and degree of urbanisation [56-60]. Sydney is a multifaceted mix of different anthropogenic activities, such as industry, commercial and agriculture, with natural areas, such as water bodies and parklands [59, 60, 65-68].

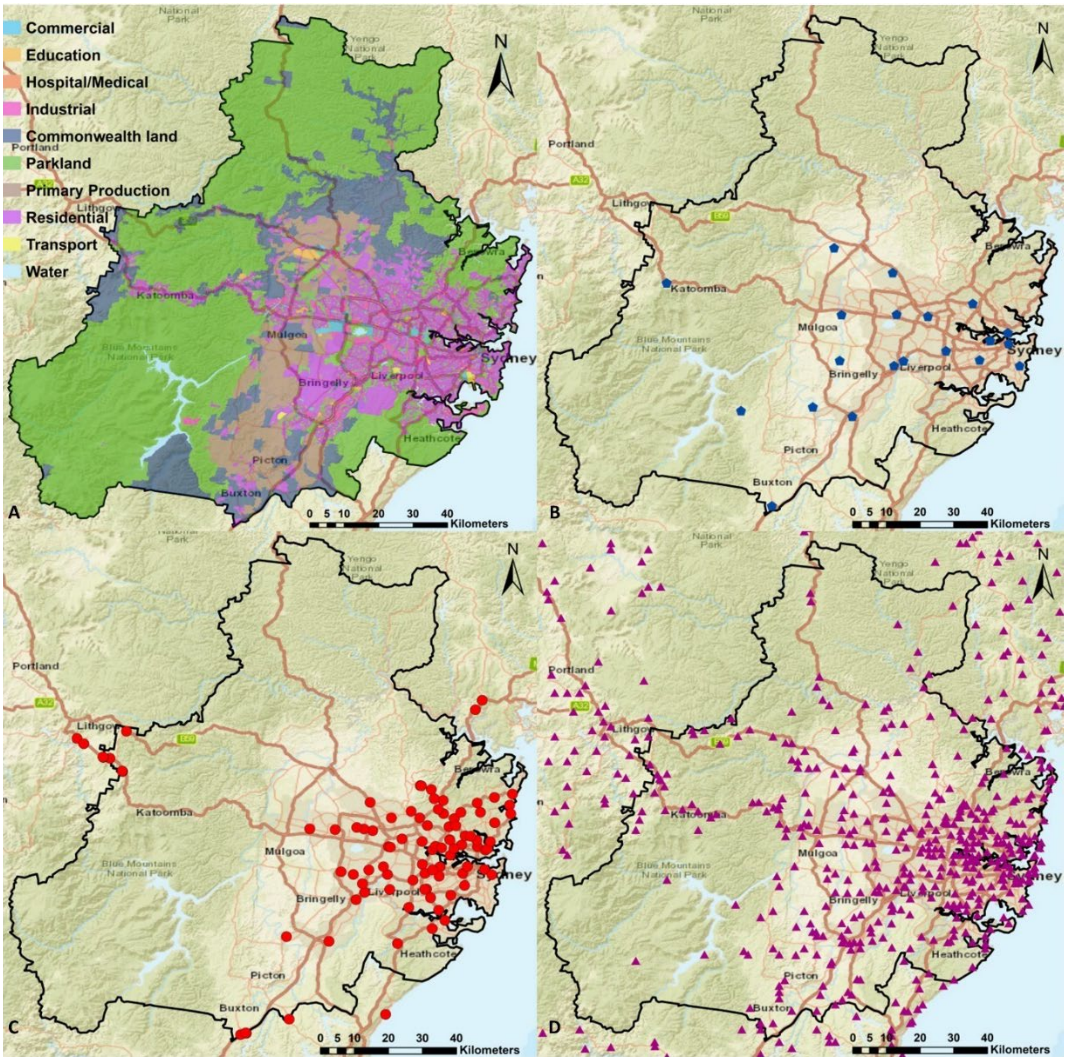


***Figure* 4.1.A.** The Greater region of Sydney study area with the land use types present in the study area [75, 204]. **B.** Office of Environment and Heritage monitoring stations are shown by the blue pentagons [70]. **C.** Bureau of Meteorology rainfall stations are depicted by the red circles [205]. **D.** Transport for NSW monitoring stations are represented by the purple triangles [206].

2. Data collection and variables

The data collected covered three different periods, each consisting of 30 days, with each period representing a different event. The natural disaster bushfire period ran from 16 December 2019 to 14 January 2020. This period was selected as it was representative of the conditions prevalent within the peak bushfire season with bushfires occurring in and adjacent to the study area [170, 207]. The local first pandemic period ran from 15 March to 13 April 2020. This period was selected due to the increased enforcement of lockdown measures and travel and industry restrictions that occurred during COVID-19 [208]. The reference control period ran from 1 February to 1 March 2020 wand was representative of the normal conditions that would occur during this time of the year. Sydney experienced the natural and pandemic disasters within a short time frame interspersed with a period of normal conditions, ensuring environmental conditions and seasonality were similar. It was confirmed that the control period was representative of a normal time period and was not influenced by the bushfires or COVID-19 through comparison with the same time periods during the previous year.

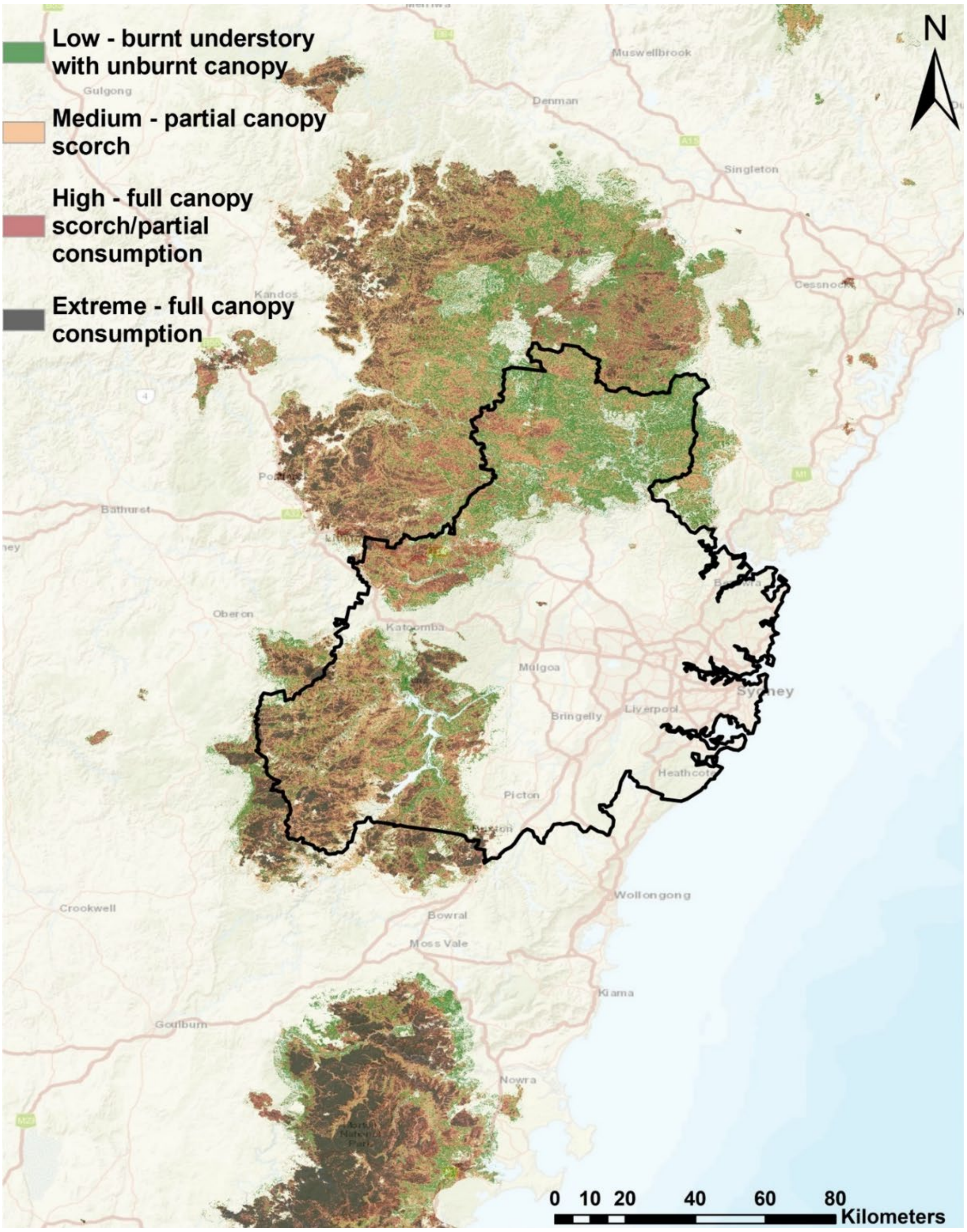


Figure 4.2. The bushfire locations, extent and severity that occurred during the Black Summer bushfires in and adjacent to Greater Sydney study area [209].

2.1 Office of Environment and Heritage monitoring – Temperature and air pollutants

Daily air pollutant concentrations and hourly temperature (°C) data were obtained from 55 Office of Environment and Heritage (OEH) monitoring stations within the study region [Figure 4.1B, [70]. The air pollutant data incorporated in this study included ambient concentrations of NO_2 (pphm) and PM_{10} (µg/m^3). NO_2 was chosen to represent gaseous pollutants, and PM_{10} was selected to represent particulate matter during the three time periods.

2.2 Bureau of Meteorology – Daily rainfall

Daily rainfall data from monitoring stations located in or around the study region was obtained from 643 Bureau of Meteorology (BOM) stations [205].

2.3 Transport for New South Wales monitoring – Daily traffic

Traffic count data from the 157 traffic counting stations shown in Figure 5.1D was obtained from the Traffic Volume Viewer provided by Transport for New South Wales [206]. The daily average traffic counts included all vehicles types and all directions of travel. The traffic counts for the bushfire period were calculated by averaging the 2019 and 2020 average counts as the sample ran across the two years. The traffic counts for the control and COVID-19 periods used only the 2020 yearly counts from each station.

3. Analysis

If the data was not already provided as daily averages, it was converted prior to processing. ArcGIS version 10.6 (Esri, 2018) was used to spatially transform and join the data, create maps and perform all spatial data analyses. Microsoft Excel 2016 (Microsoft Corporation, 2016) was used for data handling and processing, while SPSS version 26 (IBM Corporation, 2019) was used for statistical transformation and analysis. All tabular data was joined to the relevant spatial layer to ensure accurate spatial representation, and all spatial layers were transformed to the Geocentric Datum of Australia 1994, which is the Australian coordinate system [210].

Spatial interpolations for the Greater Sydney region were conducted for each variable and covariable, with a spatial resolution of approximately $500m^2$. This process was completed for each day in all three time periods for each variable, and then spatially overlaid and joined. Once all variables and covariables were spatially joined, the combined dataset was transformed and analysed in SPSS. To ensure that all assumptions were met for the repeated measures analyses of covariances (ANCOVAs), NO_2 was transformed using a square root transformation, and the PM_{10} data was natural log-transformed.

The data was analysed using repeated measures ANCOVAs for NO_2 and PM_{10}. Bonferroni's *post hoc* test was used for each air pollutant to produce pairwise comparisons and help control the high Type 1 error rate likely to arise from the large sample sizes resulting from the fine spatial resolution used in this analysis [211]. The three covariables (temperature, rainfall, and traffic count) were incorporated into the analysis to ensure air pollution during both events was accounted for. The Greenhouse-Geisser correction was used to determine significance in cases where sphericity could not be assumed [212]. All comparisons were confirmed by producing estimated marginal means (EMMs) of the concentrations from the repeated measures ANCOVAs and verified by confirming that the 95% confidence intervals for the EMMs did not intersect with the EMM from another time period [85, 213, 214].

Results

All measurements for NO_2 were within the maximum ambient concentrations set by the Department of Planning, Industry and Environment [215]. However, the daily set limit of 50 $\mu g/m^3$ for PM_{10} [215] was exceeded at one or more stations on all 30 days during the bushfire period, 17 days of the normal period, and four days during the COVID-19 period.

Spatial differences across the study site were detected for NO_2 and PM_{10} (Figures 4.3–4.5). NO_2 concentrations were CBD-centred during the normal period and generally lower during the bushfire period across the area (Figure 4.3, Figure 4.4). Interestingly, increased NO_2 concentrations were higher and more widespread during the COVID-19 period (Figure 4.5). Contrastingly, PM_{10} was concentrated to the west of the study during the bushfire period, as this area was closer to the fire areas (Figure 4.3). PM_{10} concentrations were low across the study area during the COVID-19 lockdown period (Figure 4.5), though slightly elevated across the cityscape during the normal period.

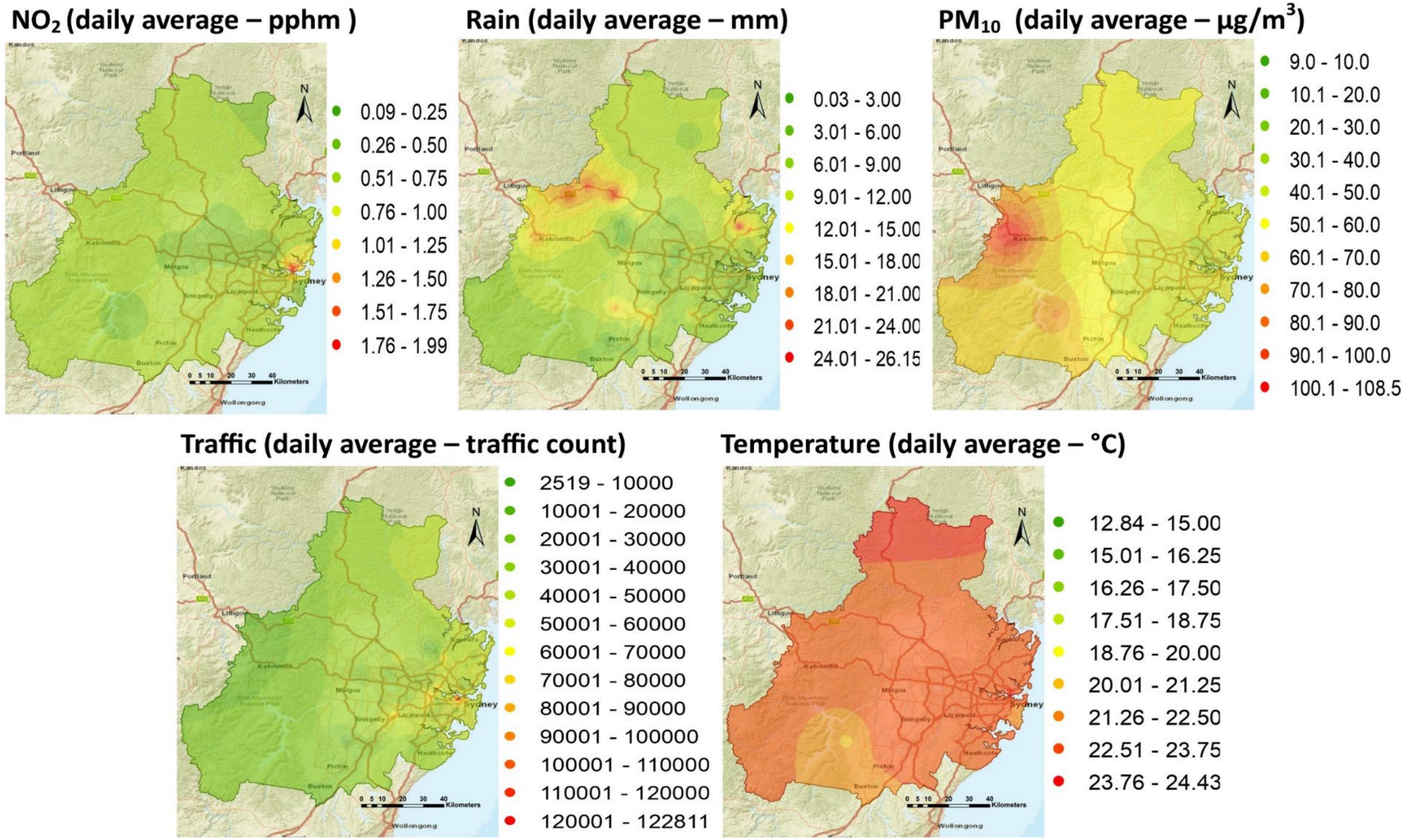


Figure 4.3. Spatial distribution for the daily average of all five variables across the study site, Sydney, the bushfire period.

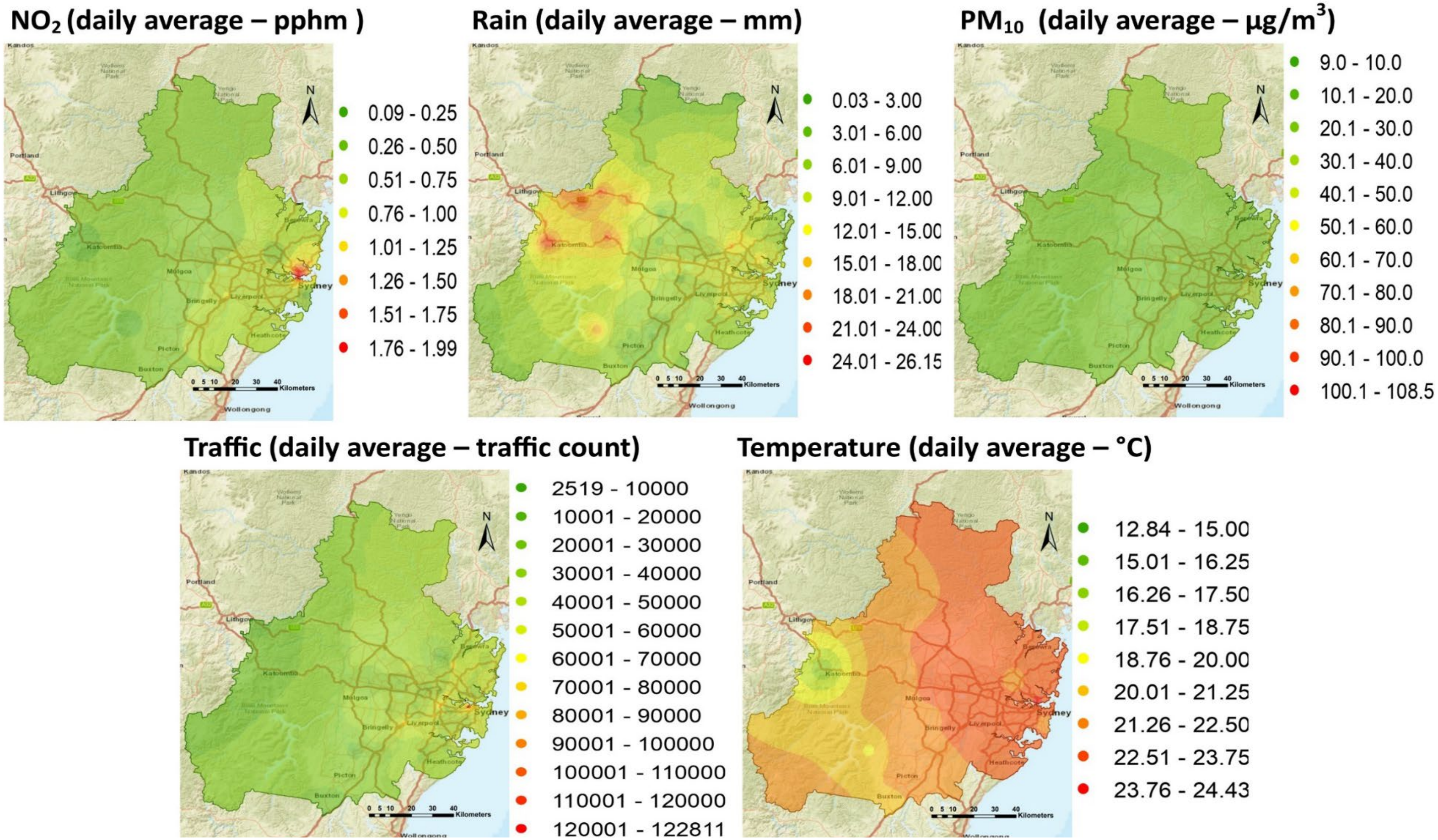
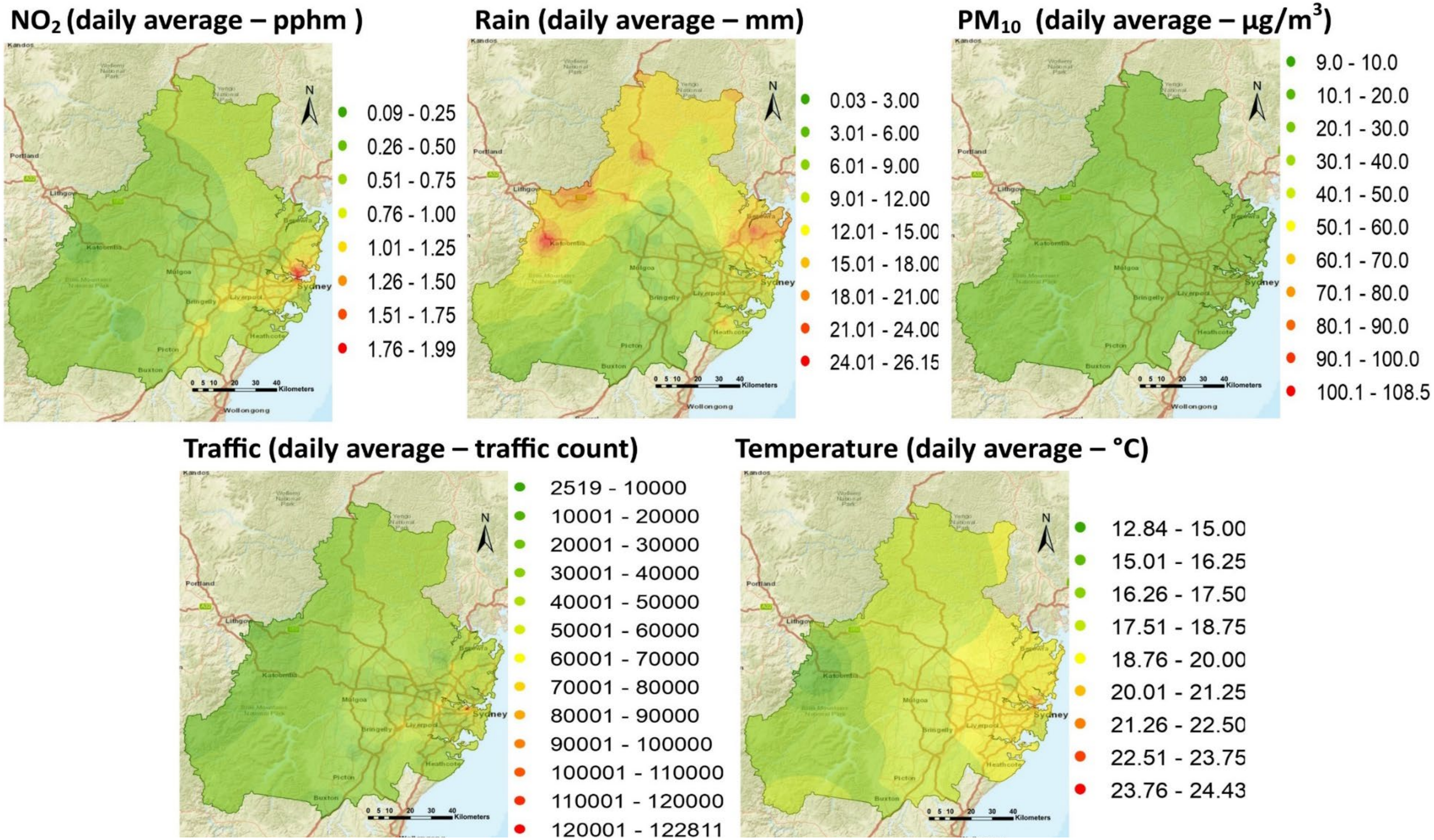


Figure 4.4. Spatial distribution for the daily average of all five variables across the study site, Sydney, during the normal period.



1795 **Figure 4.5** Spatial distribution for the daily average of all five variables across the study site, Sydney, during the COVID-19 period.

When the effects of the covariables were accounted for by the repeated measures ANCOVAs with Bonferroni's *post hoc* test, the pairwise comparisons revealed significant differences amongst the three time periods for both NO_2 and PM_{10} amongst the bushfire control and COVID-19 periods ($p<0.05$, Figure 4.6, Figure 4.7).

The results shown in Figure 4.6 show that ambient NO_2 concentrations were significantly lower during the bushfires and significantly higher during the COVID-19 pandemic. The inverse is true for PM_{10}, with significantly lower concentrations during COVID-19 restrictions and significantly higher levels during the bushfire period (Figure 4.7). The significant differences were also confirmed aby the absence of overlap between any group's EMM 95% confidence intervals.

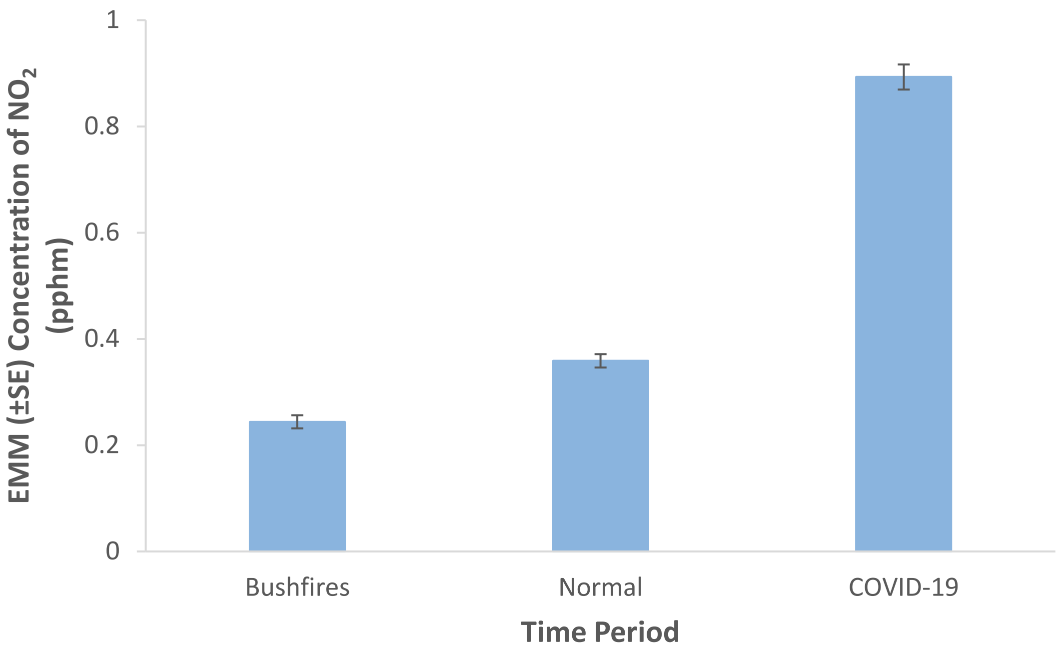


Figure 4.6. Ambient NO_2 (pphm) concentrations for the bushfire, control and COVID-19 periods. Data shown is the corrected estimated marginal means (EMM ± SEM).

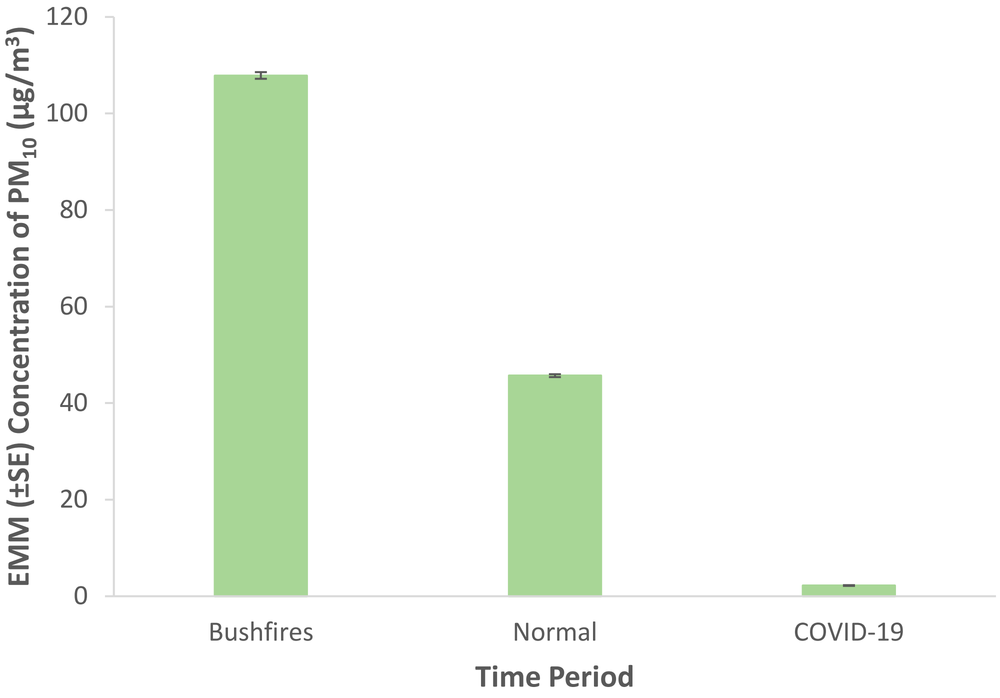


Figure 4.7. Ambient PM_{10} ($\mu g/m^3$) concentrations for the bushfire, control and COVID-19 periods. Data shown is the corrected estimated marginal means (EMM ± SEM).

Our findings demonstrate that the impacts of bushfires and the COVID-19 lockdown on air quality are not always obvious or have an equal impact on air pollution (Figure 4.8). The percentage change between the bushfire and COVID-19 and normal periods are shown in Figure 5.8. Between the bushfire and normal periods there was a decrease in NO_2, but PM_{10} experienced an increase. The opposite was true for both pollutants when comparing the COVID-19 period to the normal period (Figure 4.8).

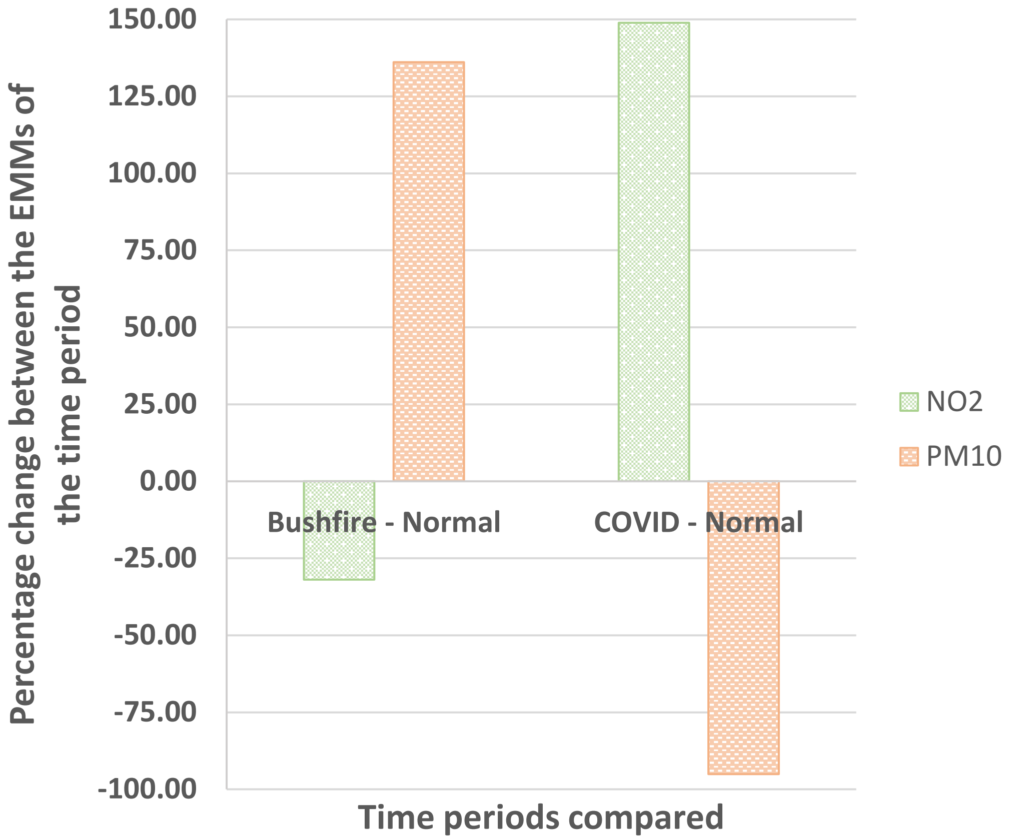


Figure 4.8. Percentages changes of estimated marginal means NO_2 and PM_{10} between the three time periods, bushfires, COVID-19 and normal.

Discussion

This study aimed to investigate the impacts of a natural disaster and global pandemic on air quality across the Greater Sydney region whilst controlling for environmental and anthropogenic variables. It builds on previous studies by furthering our understanding of natural disasters and anthropocentric events on air pollution and also explores the spatial patterns in two criteria air pollutant concentrations during these events across a cityscape. The results show that both the bushfires and COVID-19 pandemic had significant impacts on air quality, though the impact of each event differed. Interestingly, the hypothesis that lower air pollutant concentrations would occur during the pandemic was only true for PM_{10}, as there were significantly reduced concentrations of particulate matter in the Greater Sydney region in the period affected by COVID-19 in comparison to the bushfires and the control (Figures 4.5, 4.7, 4.8). However, ambient NO_2 was unexpectedly higher during the pandemic (Figures 4.5, 4.6, 4.8). As the normal period occurred between the bushfires and COVID-19, it represented as a transition time with intermediate concentrations of both pollutants.

These current findings are in contrast to those of other publications that assessed NO_2 concentrations during COVID-19, as they were higher during the global pandemic and lower during the bushfires (Figures 4.6, 4.8). Otmani *et al.* (2020) found there was a 96% reduction in NO_2 concentrations in Morocco during COVID-19, while Cadotte (2020) found significant declines in NO_2 in areas of China during government restrictions in early 2020 when compared to pre-COVID-19 levels in 2019 [216, 217]. Conversely, Iran experienced no reductions in NO_2 levels during the lockdown, and no significant NO_2 changes occurred in the period before or after the lockdown [218]. The same was observed for most sites in Greece, with no reduction in air pollution mostly attributed to the meteorological conditions that prevailed during the time [219]. The greater concentrations and wider distribution of NO_2 during COVID-19 (Figure 4.5) could have been driven by multiple factors. The reduction in the use of public transport during the pandemic and a switch in preference to commuting using private vehicles [220-222], particularly as commuters feared public transport could act as a vector for COVID-19 [223], may have influenced this.

The shift in vehicles types on Australia roads would have also impacted the air pollution experienced during these time periods as the larger vehicles with a greater polluting potential, such as SUV and light commercial vehicles, experienced increased sales in both 2019 and 2020 [224, 225]. SUVs equated to 49.6% of the sales in 2020 and 22.4% for light commercial vehicles [224, 225]. While smaller passenger vehicles sales decreased in both 2019 and 2020 [224, 225]. There additional changes in traffic experienced during COVID, characterised by the increased reliance on and movement of long-haul trucks, local fleet delivery and heavy vehicles as online purchases, deliveries and transportation of goods increased [226, 227] would also influence air pollution. Subsequently, these large polluting vehicles were the least impacted by COVID and remained consistent or increased compared to passenger/personal use vehicles, potentially equating to increased NO_2 levels [226-228]. This was further supported by the elevated concentrations of NO_2 across the city centre and the along the traffic corridors across western and Greater Sydney during COVID, while overall traffic counts remained relatively consistent (Figure 4.6).

However, vehicle transportation may be a secondary driver of NO_2 air pollution, as Wang *et al.* (2020) found the presence of industry was more strongly correlated with air quality issues including atmospheric NO_2 across China during lockdown than motor vehicles [229]. Additionally, Kerr *et al.* (2021) found that more localised and regional changes to NO_2 concentrations could be due to factors other than vehicle use, such as industrial emissions [230]. Therefore, these differences across the published literature and in this current study could be driven by the strength and severity of lockdown restrictions, transportation requirements and types, and the presence of alternative sources such as industry. Furthermore, NO_2 has a shorter atmospheric lifetime limiting its ability to disperse and accumulate, so higher NO_2 concentrations will only be observed in close proximity to bushfires [231]. This may explain why this study found NO_2 was lower during the bushfires across our area of study (Figure 4.3).

During the bushfire time period, the daily set limit of 50 μg/m^3 for PM_{10} [215] was exceeded at one or more stations on every day of the sample period. The PM produced from these natural fires would have surpassed anthropogenic sources as the primary contributing pollutant source [231]. They would have also increased as the number and extent of burning fires increased, ensuring higher concentrations of PM_{10} across the study area with increased concentrations occurring in the west of the study area due to the proximity to the bushfires (Figure 4.3). The findings of Otmani *et al.* (2020) are similar to the significant difference found in the current study for particulate matter between the normal time and the COVID-19 outbreak [216]. Otmani et al (2020) found that government restrictions resulted in a 75% decrease in PM_{10}. Likewise, Cadotte (2020) found that PM_{10} significantly decreased during the government restrictions imposed due to COVID-19 across China, Japan, and Korea [217].

The comparison between the two types of events, a natural disaster and a global anthropocentric pandemic, in this study, highlighted the unexpected differences in air quality and the need for more diverse and multifaceted approaches to handling air pollution and its associated impact on human health (Figure 4.8). Though ambient NO_2 was within guidelines for Sydney during this study, the unexpected NO_2 concentrations during COVID-19 compared to the normal time period indicate a need for continual monitoring and investigation, particularly with the potential associated human health and ecosystem health impacts [232-234]. NO2 in particular is of concern. Barnett *et al.* (2006) found a significant positive association between exposure to common urban air pollutants, such as NO_2 and PM, and hospital admissions for five types of cardiovascular disease in cities across Australia despite the levels being well below national health guidelines [233].

In reference to bushfire emissions, previous work has found that daily respiratory hospital admission rates increased as ambient PM_{10} increased and that this correlation was stronger during bushfire periods [235]. More specifically, in Sydney, a 5% increase in mortality was associated with bushfire smoke and a 6% increase in same-day hospital admissions for respiratory diseases during bushfires, with 13% and 12% increases for COPD and asthma, respectively [176, 236, 237]. Studies have also found respiratory morbidity from PM_{10} generated from bushfires was equivalent to that of urban sourced PM_{10} [238], highlighting the importance of multidimensional approaches. Additionally, those suffering from comorbidities, such as cardiovascular and respiratory illnesses, are at higher risk of adverse health effects from the PM_{10} released as ash and suspended debris created by combustion during bushfires [239, 240].

With the impacts of climate change intensifying and the severity and frequency of extremes events increasing [241], the need for countries subjected to similar climatic conditions as Australia to implement innovative and effective approaches to mitigate air pollution impacts resulting from catastrophic events, such as bushfires and pandemics, is critical to ensure the health and safety of the public [241, 242]. The impact of government restrictions during the COVID-19 lockdown on air quality were clearly detectable as the reduced human activity resulted in significantly less PM_{10} emissions. The impact of this societal change on air pollution could be used as a metaphorical starting block that could pave the way for new workplace and governmental policies that would positively benefit air quality. These findings indicate that employers could play a role in decreasing emissions by allowing employees to work from home. Additionally, employers who encourage their staff to adopt green practices and behaviours have been shown to increase these behaviours [243]. Governmental policies that lessen commercial demand, reduce transportation requirements, and alter human activity could effectively reduce urban air pollution [217]. Hence, government and workplace policies could facilitate improvements in urban air quality. Further, the implementation of early detection methods for forest fires could be used, which have the potential to predict and thus manage the associated risk with these environmental problems [244]. The outcomes of this study highlight the importance of ensuring we understand the effects of different catastrophic events on air quality to ensure the most appropriate policies are implemented.

The environmental and procedural complexities surrounding bushfire management is challenging as there is no simple approach to address these natural phenomena. A commonly implemented strategy in Australia is reducing fuel load prior to the bushfire season through prescribed burns. While these burns reduce bushfire intensity, duration, spread, smoke plume height, and pollution dispersion, they have environmental and human health trade-offs, particularly to air quality [245-252]. Additionally, the risk of bushfires in many countries has increased over time, as fire seasons are prolonged and extreme fire weather conditions become more severe as a result of climate change [245, 246, 250]. Thus, the complexities associated with bushfires emphasise the need for strong governmental support and leadership to recognise and develop transdisciplinary policies and to employ ambitious climate change mitigation targets to manage the upstream impacts of climate change on bushfire risk.

These findings also indicate a need to develop spatially relevant and adaptive policies. The traditional approaches to monitoring air pollutant concentrations, evaluating air pollution mitigation methods, and nationally sweeping guidelines must be updated as they are currently insufficient. Research has shown that local conditions should be considered when developing air pollution guidelines, along with the localised characteristics of social and economic development [253-255] Figure 4.4, Figure 4.5]. Furthermore, the importance of source-specific policies continues to grow, as broad and cost-effective general policies do not account for spatial differences in impacts incurred by source and distance from pollutant source [253, 254]. This study elucidated the impact of source, distance from source, and spatial influences and how they vary across a cityscape (Figure 4.3, Figure 4.4, Figure 4.5). Thus, they should be considered, and effectively incorporated into regionally and locally relevant policies [253-255].

Thus centralised governments, organisations and departments should continue to lead and update the standards, policies, and guidelines while simultaneously strengthening the local governments' responsibilities for atmospheric environmental protection and encouraging inter-regional strategic interaction of air pollution regulations [253-255]. Different regions also need to recognise and discern effective assessments and incentive efforts when applying nationally assessed guidelines, allowing for regional and cross-sectoral cooperation [256, 257]. Multifaceted approaches and management strategies are crucial when responding to the impacts of natural disasters and climate change or anthropocentric pandemics. They have the potential to address early warning signs, trade-offs between perceived economic risks and the greater public good, and support the potential to build partnerships between governments, private organisations and interested stakeholders, with a common focus [255, 258, 259]. As a result of the COVID-19 pandemic, research has been dedicated to developing methods of predicting the spread of disease by examining various scenarios depending on the range of people movements and interactions [260]. This has led to designated decision-making systems designed to assess epidemic parameters and predict the epidemic consequences. Some of these consequences in the name of society safety include air pollutant generating activities like; restrictions of international and domestic flights, prohibition of population concentration in groups, and a transition to remote working regime [261]. Similarly, the level of potential risk from a possible change in the environment can be made through these decision-making systems, which can be used to understand and predict future regional dynamics of both pandemic features and upcoming natural events. Using the data from the current study, future predictive models could better indicate the impacts of such events.

Studies on specific aspects of urban air pollution must take potentially confounding variables into account. The covariables included in this analysis have been previously shown to impact pollutant concentrations. Kwak *et al.* (2017) observed that PM_{10} concentrations decrease during rainfall, with the effect of rain washout being so significant that it outweighed the increased traffic pollution from slower traffic during rain. Kwak *et al.* (2017) also found that the inverse of this washout relationship is true for NO_2, as the increase in traffic emissions resulting from reduced speed outweighed the washout effects of rain [200]. Thus, rain was included as a covariable to correct for either of these confounds that rain may have produced in air pollutant concentrations.

The spatial GIS method utilised in this study accounted for geographical variations in temperature across the study area, and thus corrected for any impacts of temperature on air pollution. Kalisa *et al.* (2018) detected a positive linear relationship between both PM_{10} and NO_2 and temperature, particularly during heatwaves, where the air becomes stagnant and traps pollutants in the atmosphere [195]. Interestingly, another study that investigated the effects of forest fires on air quality in Sumatra and Borneo found a relationship between low precipitation, high temperature and air pollution [231]. Ulpiani *et al.* (2020) monitored Sydney's microclimate from December 2019 to January 2020, and confirmed that drought, heatwaves, and high pollution levels occurred alongside the bushfires [262]. This relationship between low rainfall, high temperatures and air pollution was also seen during the bushfires investigated in this current study, and these conditions would have contributed to the prolonged duration and high intensity of the fires, supporting the inclusion of these meteorological covariables in this study.

This study, however, did not consider industrial sources of pollutants, nor wind speed and direction. It would be of value if future studies could incorporate these effects as covariables due to their potential influence on ambient pollutant concentrations [195]. Additionally, the investigation of other pollutants and the incorporation of health impacts would improve the understanding of these events on human health. Also, the addition of paired spatial tools or GIS techniques to integrate additional covariables and geographical factors [263] might reveal additional trends. Ultimately, the current study provides valuable information to assist enterprises and government organisations in developing new regulations and standards for addressing green behaviours, air pollution, and associated health impacts [178]. The development of multifaceted approaches would also add to the resilience of the impacted sectors and assist with the recovery of these industries in a more sustainable way.

Conclusion

This study is one of few to spatially analyse the relationship between air pollutants during the regionally-relevant natural bushfire disaster event in comparison with the global pandemic. Meteorological factors and traffic were included as covariables to ensure the effects of these events on air pollution were investigated. This study showed significantly higher concentrations of PM_{10} during the bushfire period than during normal times, and significantly lower PM_{10} during COVID-19 restrictions. The reverse was found for NO_2, as there was significantly less ambient NO_2 during the bushfires and more during the COVID-19 period. The surprising findings have highlighted the need for multifaceted policies and approaches when mitigating air pollution and ameliorating air quality during extreme events, particularly as these types of events will increase in more frequency and severity in the future. The need for spatially interwoven and mutually supportive standards and guidelines will be vital if air pollution mitigation strategies are to be successful as urban development increases. Future studies should examine the response of other pollutants during these extreme episodes, while more spatially relevant variables should be investigated to understand the impact they have on air pollution during these events. Furthermore, this study has highlighted the strong and unique impacts of regional and global events on air quality and the need to re-evaluate single faceted approaches if we wish to manage air pollution during these extreme and challenging crises.

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5. The Green Wall Wish: Understanding Public Perception, Willingness To Pay, And Barriers To Local Green Wall Development In Australia

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Abstract

The densification of cities negatively influences urban populations globally, with impacts ranging from reduced human health to declining biodiversity. To overcome these adversities, urban centres must act towards mitigating effects attributable to urbanisation. Natural environments and planted landscapes are a key component missing from many urban centres. One potential strategy to improve the environmental quality of urban centres is to increase the prevalence of green infrastructure initiatives such as green walls. Green walls are gaining in popularity globally, as not only do they address these concerns, but they are spatially efficient and provide a range of additional benefits. Currently, barriers and obstacles exist that impede the

uptake of green walls across urban regions, including those in Australia. Consequently, this study was undertaken as a preliminary exploration of Australia´s acceptability of green walls by investigating the general public's awareness, experience, and perception of green walls, barriers to implementation, and willingness to pay for local green wall development. This was achieved by distributing a survey to local government and voluntary councils and through council e-newsletters. Survey responses were grouped by the demographic characteristics of the respondents to potentially identify the attitudes of different groups within Australian society. The outcomes of this survey revealed a consensus that greener cities are worthy of increased investment. While only 17% of participants spent significant time near green walls, most viewed them positively due to their perceived benefits and the emotional and restorative responses they evoke. The most important benefits include improvements to air quality, beauty, and aesthetics, as well as a reduction in the urban heat island effect. The most frequently reported responses were feeling more at peace and having a stronger sense of community pride and belonging. These varied significantly across gender, age, income and geographic region. Most participants reported that having a green wall at their place of work, study, or residence would likely improve their quality of life and were willing to pay for local green wall development. However, the amount that participants were willing to invest differed with income, where those earning a median to high income were more willing to invest at the highest threshold, and those in the highest income bracket were the least likely to invest. This exploratory study highlighted two barriers to local green wall development: the primary assistance requested by participants was educational and technical resources (guidance, workshops, technical support), and the secondary assistance was fiscal (rebates, funding, incentives). The highest-ranked considerations that would facilitate local green wall development included ease of operation and structural durability and maintenance, however, these varied substantially across gender, age, income and geographic region. This exploratory study provides preliminary evidence that the Australian community wants to develop green walls at or near their residence. However, barriers to implementation must be addressed through greater educational, technical and fiscal support from different levels of government or private industry to provide the necessary resources. Providing these may pave the way for a greener Australia.

Introduction

Rapid urbanisation and densification is a global issue attributable to poor city planning, increased population growth, and the expansion of urban sprawl [264, 265]. Urban areas currently home 56% of the world's population, a figure that is predicted to rise to 68% by 2050 [266]. This is a growing cause for concern due to the associated impacts of urbanisation such as declining vegetation and biodiversity, increased stormwater runoff, greater air and noise pollution, and the urban heat island (UHI) effect, which all exert social, economic and environmental pressure on city residents [24, 264, 266-270]. These impacts also have secondary effects, such as a greater demand for building cooling, increased energy consumption, increased health problems and physical and mental discomfort [271-273]. Thus, there is a requirement for the integration of ecologically sustainable practices into existing infrastructure to assist in amelioration and mitigation of the detrimental effects of urbanisation [274]. Consequently, governments, local authorities and urban planners globally are demonstrating a growing willingness to address the detrimental effects of urbanisation by assessing risks, formulating plans, and investigating innovative approaches to mitigate these impacts [34, 275]. With 86% of Australia's population currently living in urban areas, Australians are likely to experience increasingly severe impacts as the proportion of the population living in urban conditions is forecasted to increase to 91% by 2050 [276].

Given the impacts of urbanization, as well as the requirement to peruse livable cities, the need for integrating sustainable and green approaches into new and existing urban developments has become apparent [269, 274]. Green infrastructure (GI) is gaining in popularity globally as it is a means to counteract the declining vegetation and can be integrated into existing building designs or retrofitted after construction or implemented into the urban landscape [34, 93, 120, 277]. The term green infrastructure covers a range of different greening projects and types, such as vertical green systems, green roofs, urban forestry, or other sustainable urban projects [191, 277, 278]. For this exploratory study, the main focus was green infrastructure in the form of vertical greening systems, commonly known as green walls (GWs), that are integrated externally into the buildings' envelope during construction or retrofitted afterwards [277]. Vertical greening systems can also range in both application and complexity of design, from the use of climbing plants planted directly into the ground or in planters at various heights or the base of the wall to complex or modular systems which hold their own planting substrate vertically but also require complex setups regarding maintenance, irrigation and supporting structures [277, 279-281].

GWs reduce impacts associated with urbanisation and considerably reduce the need for specific land allocation, a scarce resource in urban environments. The most notable benefits of GWs include a decreased UHI effect and subsequent building energy consumption reductions [13, 279, 282, 283], improved stormwater control and management [284-287], increased biodiversity and conservation [288-290], enhanced air quality [291-293], reduced noise pollution [24, 160, 290, 294], and improved mental health and wellbeing [295-300].

Effective communication of these benefits may improve the public's knowledge and garner a greater support for green infrastructure in their communities [301]. Social acceptability helps bridge the gap between potential and actual implementation, particularly when integrating new or alternative solutions and technologies [302-306]. Social acceptance also helps reframe the potential barriers to implementation, particularly with financial or educational barriers [302-306]. This is particularly important as the public's involvement, and engagement is necessary to increase green wall implementation [307-309]. Consequently, a greater understanding of factors that influence the public's perceptions, knowledge and use of GI is essential. Previous studies have shown that multiple factors influence this perception. The different categories of factors include institutional factors like level of awareness of GI and involvement in planning [284, 301, 307, 310-312]; socio-economic factors, including employment types, living arrangements or housing types/areas, income and education level [284, 313-317]; demographic factors such as gender and age [318, 319]; and bio-physical characteristics of the GI itself, including the type and size of GI, the location and perceptions of safety [307, 320, 321].

Regions that have worked to overcome some of these challenges include Europe and North America, where GI has been increasingly implemented mainly through the retrofitting of existing buildings in urban areas [322, 323]. In contrast, GI technology has been much less frequently implemented in Australia, with cities at an earlier developmental stage than many other countries, and consequently, GW uptake in Australian cities is comparatively low [34]. This could be due to the differences in governmental policies and support. Internationally, higher-level Government instruments and support, such as policies, regulations and standards, and financial incentives, have been widely implemented and appears to be driving the increase in GI projects [34, 322, 323]. The success of these could be driven by the greater potential funding and increased social acceptability and awareness of the associated benefits of these nature based solutions across a greater spatial scale. On the contrary, the majority of Australian building and development standards and policies occur within the local council jurisdiction, which is the lowest level of government in Australia and has the smallest jurisdictional reach [34, 323]. As socio-political acceptance increases globally, many international policies relating to GWs and GRs (green roofs) occur across numerous jurisdictional levels [34, 306, 322], and the effect upon the rate of

GI implementation is evident. Furthermore, evidence for effects that influence GI implementation is supported by research and case studies which are predominantly from Europe and North America [34, 322-324]. The reliance on Northern Hemisphere research is an additional barrier in Australia due to significant differences in temperature, suitable vegetation and rainfall, particularly as the success of green wall projects are dependent on the climate-specific plant selection, resilience, and maintenance [323, 324]. This is further compounded by Australia's long distances between cities. Consequently, the cities experience drastically different climates as Australia experiences six different climatic zones from tropical climates to arid deserts [324, 325]. The combination of these factors and the endemic nature of our flora and fauna results in incompatibilities when applying research uniformly across the continent.

Additionally, the green infrastructure industry in Australia is currently small and highly risk-averse [34, 323, 324]. This could be due to reliance on the northern hemisphere research and the associated problems stemming from an isolated or inaccessible supply chain [34, 323]. Additionally, green infrastructure is seldom included in Australian green building ratings schemes or sustainability planning policies [323]. Thus, the development or inclusion of green infrastructure in planning policies will strengthen this developing industry. The development of green infrastructure industry standards in Australia would also assist with establishing new business and creating new companies and market opportunities while promoting stronger linkages between research, industry, and government sectors [323, 324].

In summary, in Australia, the barriers to GW uptake may include a lack of awareness of the known benefits as there are very few successful examples of GW projects; a lack of industry standards relating to GW construction; a general absence of green infrastructure (GI) policies and guidelines; relatively few companies and professionals capable of installing and maintaining GWs;

and little research associated with GWs in the varying Australian climates across each city [34, 323].

To understand this further so as to overcome these obstacles, we performed a nationwide exploratory study aimed at investigating the public's current levels of awareness, experiences and perception of GWs, their willingness to pay (WTP) for local GW development, and potential barriers to implementation. This was achieved by distributing a voluntary survey to members of the Australian public through governing bodies across the continent, which investigated these attributes as well as the survey participants' demographics through a series of multiple-choice and open-ended questions. Survey data was then analysed to understand general and demographic-specific trends. In doing so, we interpreted the data so as to identify common conceptions and misconceptions around GWs, which will aid in supporting and marketing GW development to the appropriate demographics.

Methodology

1. Survey Distribution

In an attempt to gather representation for this exploratory study, an Australia-wide survey was distributed in 2019 to 397 local governments (of 537 total in Australia) and seven voluntary councils. It was also listed in two council e-newsletters (see Appendix Table 5.3). These governments and councils were selected and contacted based on their capacity to effectively communicate with the local residents of their respective areas, as they have the closest relationship with their residents and the most interactions. Local governments in Australia are the third and lowest level of governing division and are responsible for services such as local infrastructure, recreational facilities, and health services. The voluntary councils are not-for-profit community councils that function in the role of local governments by serving the interests of citizens within their boundaries whilst lacking the legislative and regulatory powers and responsibilities of the local government councils. The governments and councils were asked to subsequently distribute the surveys to any individuals, local green companies or community groups that they thought may be interested in participating in the survey within their jurisdictions. This was distributed through their social media platforms, community newsletters e-newsletters and appropriate emailing lists. The survey was open for five weeks, from early July to August 2019, and 161 individuals submitted responses.

2. The Survey

The survey featured 37 questions; 12 were pre-defined response options relating to the participants' awareness, experiences, and perception of GWs and WTP for local GW development, 19 featured open-ended responses, which were assessed to contextualise the reasoning for the pre-defined response options and/or used to obtain more subjective and personalised information, one was for administration purposes, and five related to the following demographic criteria: age, gender, gross annual income, highest level of education, and residential postal code. The open-ended questions were included to assist with understanding the level of social acceptance of GWs, the competing social and economic priorities and interests and the influence of the potential barriers to GW implementation. The survey questions were developed based on previously published surveys to ensure an understanding of the respondents was gained for this preliminary survey into Australia's acceptance of green walls while minimising any potential influences of the questions themselves and survey fatigue [326-328]. Postal codes were categorised by the Accessibility/Remoteness Index of Australia (ARIA), which classifies area codes based on their distance from Australian service centres [329]. The more remote the classification, the reduced accessibility to goods, services and opportunities for social interaction. For example, major city residents were considered to have relatively unrestricted accessibility to a wide range of goods, services, and opportunities for social interaction, while remote residents had very restricted access to goods, services, and opportunities for social interaction. To ensure that the survey did not influence participants, no additional information was provided about GWs or GI in general, thus investigating the public's current level of awareness, experiences, and personal perception of GWs, as well as their willingness to pay for local GW development and potential barriers to implementation, as per the aims.

3. Statistical Analysis

To determine whether survey responses differed across demographics and elucidate barriers to GW development, responses were collapsed to the demographic categories presented in Table 5.1 below. Further, surveys featuring multiple blank responses were removed, and questions with multiple response options were collapsed into categories, as seen in Table 5.2. Prior to removal, the respondents with missing data were evaluated and checked for potential biases to ensure deletion was the most appropriate method. This removal of data also minimised potential issues associated with extrapolation from missing data. The categories created for various question responses in both Table 5.1 and 5.2 were created on a compromise between census data and government definitions and quantiles from our own data, while categories for the open-ended response questions were created based on the data received and expected responses noted in previously published literature [326-328]. Pearson chi-square tests for independence with Monte Carlo simulations were used to examine differences across the five demographic groups. This technique was utilised as >20 % of cells had expected counts <5 across several Pearson chi-square cross-tabulations. Monte Carlo simulations were performed for all comparisons using 1000 permutations, and statistical significance was determined at $P < 0.05$. The questions included in the analysis are summarised in Table 5.2. Data was analysed using R-project statistical software [330].

Table 5.1 Demographic characteristics of respondents (n = 131). Reference terms are given to indicate the alternate language (if any) used throughout this study to describe each modality.

Demographic	Modalities	Reference	Freq.	Perc. (%)
Accessibility/Remoteness Index of Australia (ARIA)	Major City		95	72.5
	Inner Regional		18	13.7
	Outer Regional		13	9.9
	Remote		5	3.8
Age (years)	18-35	Young	34	26.0
	36-55	Middle-aged	64	48.9
	>56	Elder	33	25.2
Gender	Male		38	29.0
	Female		93	71.0
Gross annual income (AUD)	$0-40,000	Low	20	15.3
	$40,001-80,000	Median	44	33.6
	$80,001-120,000	High	35	26.7
	>$120,000	Higher	6	4.6
	Prefer not to disclose		26	19.8
Highest level of education	High school		12	9.2
	Undergraduate		84	64.1
	Postgraduate		32	24.4
	Other		3	2.3

Table 5.2 Survey questions included in analysis (n = 131). Key term(s) are underlined and bolded to indicate reference term used throughout this study to refer to each survey question. Initial answers for each of the recategorised answers are indicated in brackets.

Survey question	Initial Answers	Recategorised answers
Is this the first time you have heard of green walls?	1. Yes 2. No	
Which level of awareness best describes your understanding of green walls?	1. No awareness of green walls prior to this survey 2. Seen or read something about green walls 3. General understanding of green walls 4. Strong interest in green walls 5. Working in an area involving or related to green walls	1. Low (1, 2) 2. Moderate (3) 3. High (4, 5)
Do you live or work near a green wall?	1. Yes 2. No	

Were there any <u>features</u> that you <u>liked</u> on any of the green walls you have seen?	1. Yes 2. No
Were there any <u>features</u> that you <u>disliked</u> on any of the green walls you have seen?	1. Yes 2. No
What are the <u>benefits</u> of green walls that are most important to you? **Improved <u>Air Quality</u>** **Beauty and <u>Aesthetics</u>** **Increased <u>Biodiversity</u>** **Improved <u>Health</u>** **<u>Insulation</u> for Buildings** **<u>Noise</u> Reduction** **Reducing Urban Heat Island (<u>UHI</u>) Effect** **<u>Stormwater</u> Management**	1. Yes 2. No
Would you like to see <u>more green walls</u> in the area where you live, or around your place of study/work?	1. Yes 2. No

Where would you like to see <u>more green walls</u>; in the area where you live, or around your place of study/work?	1. Live (near my home) 2. Work/study (near my work or educational institution)	
What would you be willing to spend in order to construct a 3m x 3m green wall at/near your property?	1. $0 2. $1-200 3. $201-400 4. $401-600 5. $601-800 6. $801-1,000 7. >$1,000	1. $0-400 (1, 2, 3) 2. $401-800 (4, 5) 3. >$800 (6, 7)
Do you wish <u>Australian</u> cities followed the lead of some other countries and became <u>greener</u> through green wall installations?	1. Yes 2. No	
Are you more likely to <u>feel</u> any <u>different</u> when you are in an area with a green wall? If yes, then how so? Please tick the following: **<u>Safer</u>**	1. Yes 2. No	

More <u>sociable</u> **More at <u>peace</u>** **A stronger sense of <u>community pride</u>** **A stronger sense of <u>belonging</u> to your <u>community</u>** **<u>Other</u> feelings**		
If you were to develop a community centred green wall, to what extent are the following considerations <u>important</u> to you and/or the community? On a scale from 1 (not important) to 5 (very important). **<u>Budget</u>** **<u>DIY friendly</u>** **<u>Easy to integrate</u> onto the wall** **<u>Low maintenance</u>** **<u>Easy to operate</u> (drainage, maintenance and irrigation system)**	1. Not important 2. 3. Moderately important 4. 5. Very important	1. Low (1, 2) 2. Moderate (3) 3. High (4, 5)

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Self-sufficient drainage and irrigation system
Community engaging
Aesthetically pleasing
Easy to source materials
Made of recycled materials
Use recycled water as its primary water supply
Sustainability
Water Efficient
Modular system enabling versatility to scale up
Structurally strong and weather resistant

Results

1. Demographic characteristics of participants

Survey respondents resided predominantly along Australia's coastline, with the majority from the state of New South Wales (38.9 %), followed by Victoria (32.8 %), Western Australia (10.7 %), South Australia (8.4 %), Australian Capital Territory (3.8 %), Tasmania (3.1 %) and Queensland (2.3 %) (Figure 5.1). There were no respondents from the Northern Territory (Figure 5.1). The distribution of respondents closely reflects the country's population density.

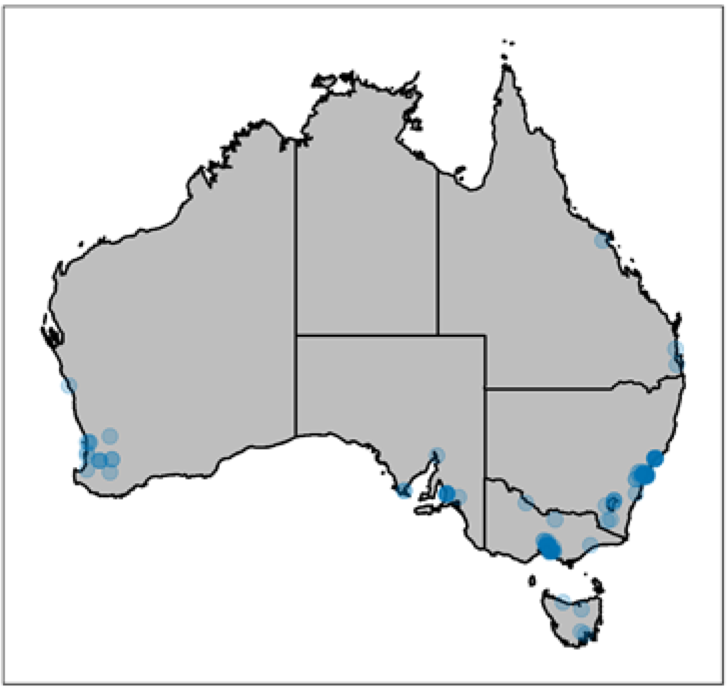

Figure 5.1. Distribution of survey respondents within Australia.

The final sample comprised 131 eligible participants who were more likely to reside in a Major City of Australia (72.5%; Table 5.1), be 36-55 years of age (48.9%; Table 5.1), identify as female (71.0%; Table 5.1), earn a gross annual income of $40,001-80,000 AUD (33.6%; Table 5.1), and possess an undergraduate qualification as their highest level of education (64.1%; Table 5.1).

Amongst the cohort, several responses significantly differed amongst the demographic criteria. These effects are summarised across the five demographics in Figure 5.2, which shows the distribution of statistically significant comparisons amongst survey responses.

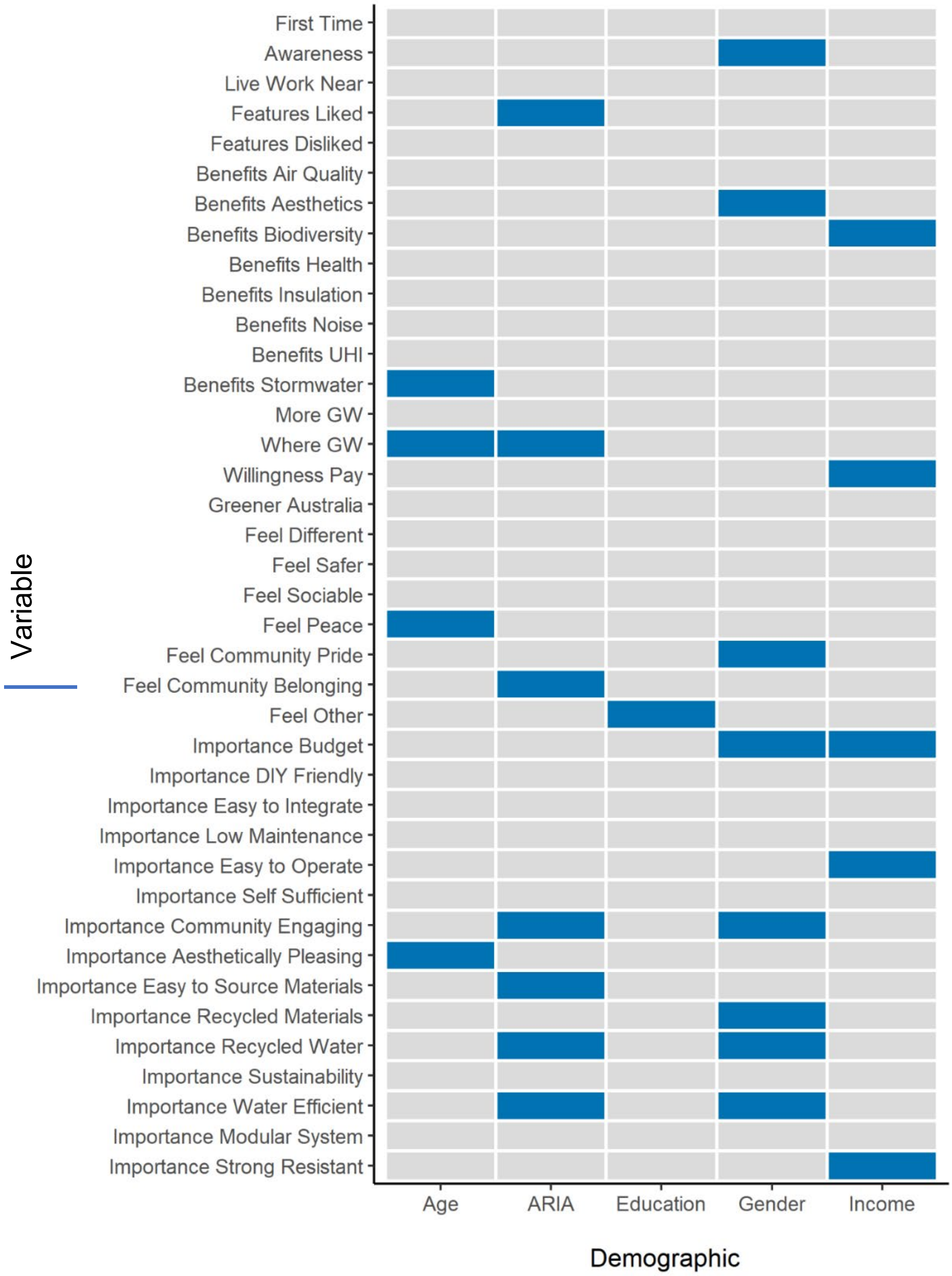

Figure 5.2. Heat map depicting significant (P < 0.05, blue) and non-significant (grey) Pearson Chi-square tests of independence with Monte Carlo simulations (B = 1000). The blue cells indicated a significant association between the green wall variable and the population demographic.

2. Green wall awareness, experience, and perception

Most participants had heard of green walls (GWs) prior to the survey (86.3%), with no significant differences in basic awareness among any demographic criteria (Figure 5.2). Most frequently, participants reported moderate GW awareness (36.6%), though females reported greater levels of awareness than males (52.9 vs 25.7 %, p = 0.026), with no significant differences across remaining demographics (Figure 5.2). Most did not live or work near a GW (83.2%), which was consistent across all demographics (Figure 5.2). However, many reported that they liked at least one feature of GWs (72.3%), though this varied amongst Accessibility/Remoteness Index (ARIA) criteria; that is, participants living in a Major City reported that they liked a GW feature(s) significantly more than remaining regions (81.1 vs 60.0, 55.6, and 46.2 % for Remote, Inner Regional, and Outer Regional ARIA respectively, p = 0.011). Contrastingly, participants who reported low-moderate dislike for a GW feature(s) were consistently distributed across all demographics (~32.8%).

Participants were asked to rank commonly identified benefits of GWs on a scale from low to high importance. The most highly regarded benefits included improved air quality (81.7%), beauty and aesthetics (78.6%), and reducing the urban heat island effect (72.5%, Figure 5.3). Females identified beauty and aesthetics as an important benefit of GWs more frequently than males (83.9 vs 65.8 %, p = 0.037). Young participants identified stormwater management as an important benefit more frequently than middle-aged and elder participants (44.1 vs 34.4 and 15.2 %, p = 0.040). A greater proportion of low-median income earners identified increased biodiversity as an important benefit than high- and higher-income earners (60.0-61.4 vs 40.0 and 0.0 %, p = 0.031). The perception of remaining benefits was distributed similarly across demographics (Figure 5.3).

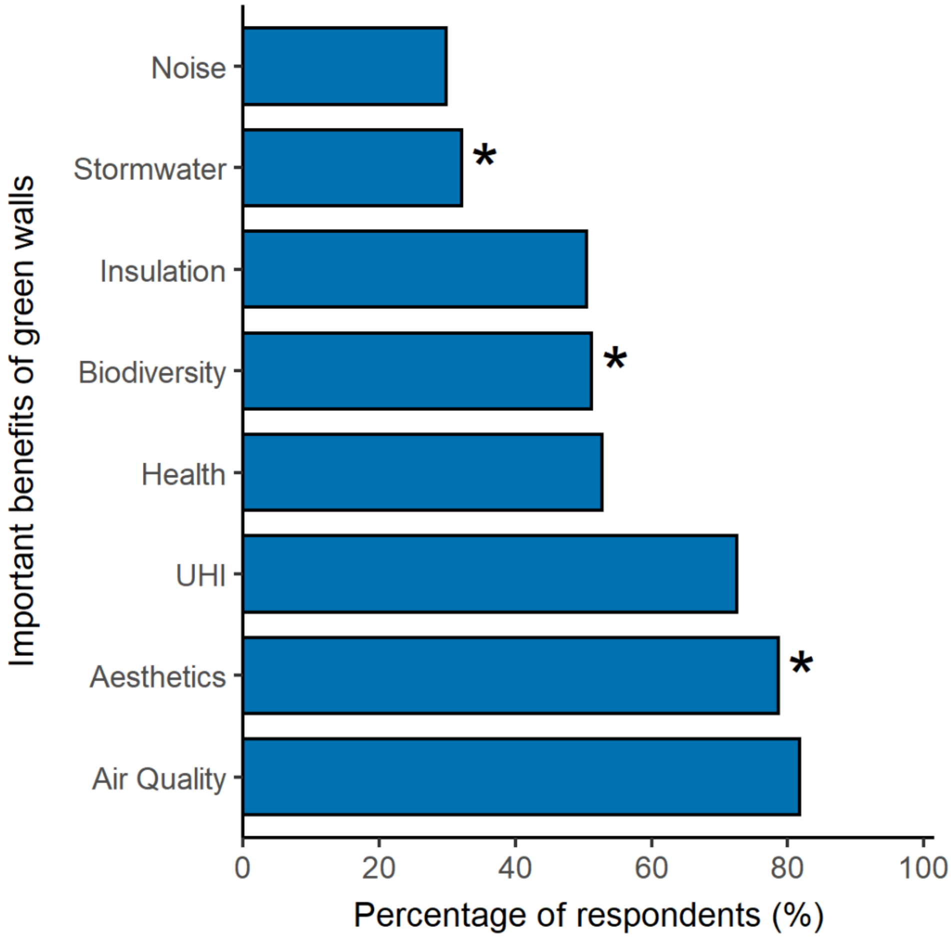

Figure 5.3. Distribution of respondents who selected each green wall benefit as highly important (n = 131). Asterisk denotes significant Pearson Chi-square tests of independence with Monte Carlo simulations (B = 1000) across at least one demographic criteria.

Participants were asked to report whether they felt different in the presence of a GW and with which emotional and restorative response(s) these feelings resonated. The majority of participants reported they were more likely to feel different in the presence of a GW (95.4%). The most frequently identified responses included being more at peace (80.2%), a stronger sense of community pride (58.0%), and a stronger sense of belonging to their community (28.2%, Figure 5.4). A greater proportion of females reported a stronger sense of community pride when in the presence of a GW than males (69.9 vs 28.9 %, $p = 0.001$). Young participants identified feeling more at peace when in the presence of a GW more frequently than middle-aged and elder participants (91.2 vs 71.9 and 84.8 %, p = 0.036). Participants residing in Remote Australia reported feeling a stronger sense of belonging to their community when in the presence of a GW more frequently than Major City, Inner and Outer Regional residents (80.0 vs 28.4, 16.7, and 23.1 %, p = 0.037). Participants with postgraduate and undergraduate qualifications reported other feelings elicited by being in the presence of GWs more frequently than those with high school and other qualifications (16.7 and 34.4 vs 0%, p = 0.034). The perception of the remaining responses elicited by GWs was distributed similarly across demographics (Figure 5.4).

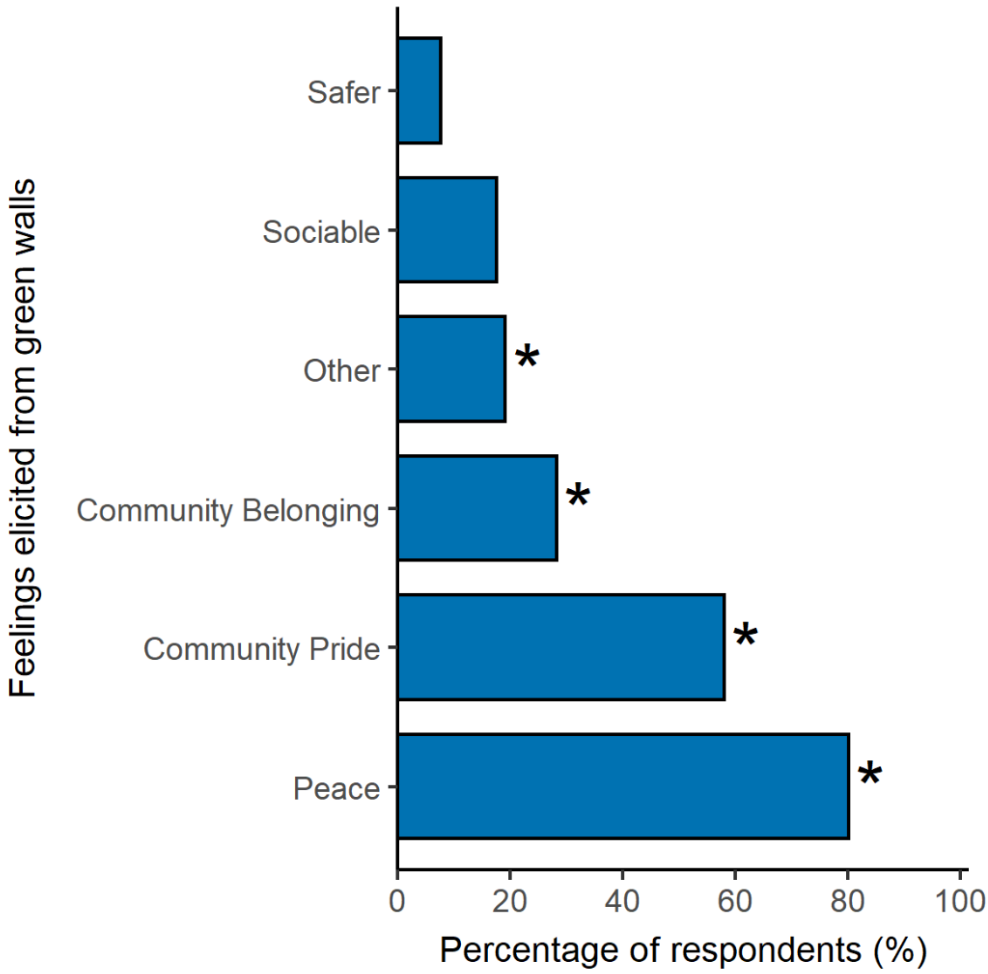

Figure 5.4. Distribution of respondents who selected each feeling elicited from being in the presence of a green wall (n = 131). Asterisk denotes

significant Pearson Chi-square tests of independence with Monte Carlo simulations (B = 1000) across at least one demographic criteria.

Most participants reported that they wished Australian cities followed the lead of other countries by becoming greener through GW installations (96.9%). All participants reported that they would like to see more GWs in the area they live study/work. This was consistent across all demographics (Figure 5.2), however, the areas in which participants would like to see more GWs differed significantly amongst age ($p = 0.026$) and Accessibility/Remoteness Index (ARIA) criteria ($p = 0.004$) criteria; young-middle aged participants preferred to see more GWs in the area that they study/work (58.8-60.9 %), whereas elderly participants preferred to see more GWs in the area that they live (66.7%). Participants who reside in Inner Regional and Remote Australia had similar preferences, where most reported that they would prefer to see more GWs in the area that they work/study (61.6 and 60.0 %). Participants who reside in a Major City had roughly split preferences for GW location between the area that they live (54.7%) and area that they work/study (45.3%), whereas participants who reside in Outer Regional region reported that they would prefer to see more GWs in the area that they work/study (100%). Nevertheless, most participants (71%) believed that having a GW at their place of residence would improve their quality of life, and a further 10% agreed if certain conditions were met (for instance, if the GW featured vegetables, fruits or herbs).

3. Willingness to pay for local green wall development

The majority of participants reported that they would be willing to pay for the construction of a 3 m x 3 m green wall at/near their property (92.4%). Most (70.2%) elected that they would be willing to invest $0-400 AUD towards GW construction, with 22.9% and 6.9% willing to invest between $401-800 and >$800 respectively (Figure 5.5). This was consistent across all demographics, with no significant differences shown, except income (Figure

5.2, p = 0.031), where participants earning a high salary ($81,000-120,000) had the most frequent incidence of investing >$800 AUD (17.1%), followed by median (12.5%), low (9.1%), and finally higher-income earners (0.0%; Figure 5.5). Additionally, participants who preferred not to disclose their income had no incidence of willing to invest at the higher bracket (0.0%, Figure 5.5).

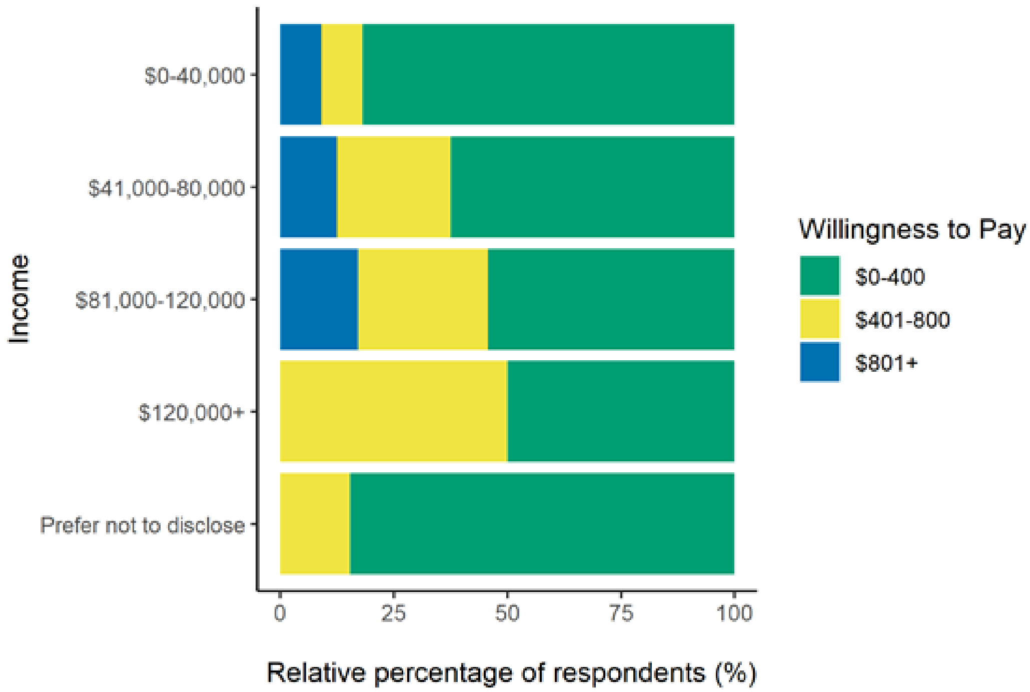

Figure 5.5. Willingness to pay for local green wall development of respondents belonging to various income brackets (n = 131).

4. *Potential barriers to local green wall development*

The most reported reason for not selecting a higher monetary contribution to personal GW development was related to personal budget constraints and financial limitations (39.7%), contrasting to a degree with the willingness to pay behaviour of the different income brackets. Other reasons included uncertainty around requirements for GW construction (4.6%), more appropriate green options available or the surrounding area was already green (5.3%), and/or the price range selected was thought to be reasonable or appropriate for local GW construction (16.8%).

The majority (82.4%) of participants stated that they would possibly consider constructing a GW if their workplace and/or local council encouraged or assisted with its construction. Contrastingly, 13% of participants stated that they were unsure or would not consider constructing a GW. The predominant reasons given were the need for more information (20% of those responses), the property or ownership of the property being inappropriate (15%), or the preferences for somewhere else to be greened (20%).

The majority of participants (68.70%) identified the provision of more information as the primary assistance required from their local council and/or employer to encourage them to build their own GW (for instance, guidance/advice, workshops, technical support/consults). This was further highlighted by respondents requesting the following information: construction and design plans (37.78% of the information-based responses), advice on appropriate plant species selection (11.11%), maintenance regimes (7.78%), and local building codes and/or practices (10%). The secondary assistance type required was identified as fiscal (39.69% of participants) in the form of rebates, funding, subsidies, incentives and/or grants. With the third being resources (22.14% of participants) in the form of plants, building materials, labor/skills, and use of equipment.

When queried on what considerations were important to the participant and/or their community if they were to develop a community centred GW, responses varied substantially across all demographics except education (Figure 2). The most frequently identified considerations for GW development included requirements for systems being easy to operate, particularly as related to drainage, maintenance and irrigation systems (77.1%), structurally strength and weather resistance (76.3%), and low maintenance (74.8%; Figure 6).

Gender was significantly influential on the ranking of considerations for GW development, where female participants ranked the following considerations as highly important significantly more so than males; budget (43.0 vs 15.8 %, p = 0.004), community engagement (51.6 vs 34.2 %, p = 0.032), made of recycled materials (62.4 vs 34.2 %, p = 0.013), using recycled water as a GWs primary water supply (66.7 vs 36.8 %, p = 0.005), and water efficiency (76.3 vs 52.6 %, p = 0.020). Conversely, male participants did not show strong support for any considerations that were not similar or exceeded by females. Elderly participants ranked being aesthetically pleasing as a highly important consideration for GW development significantly more so than young-middle aged participants (75.8 vs 61.8 and 64.1 %, p = 0.030).

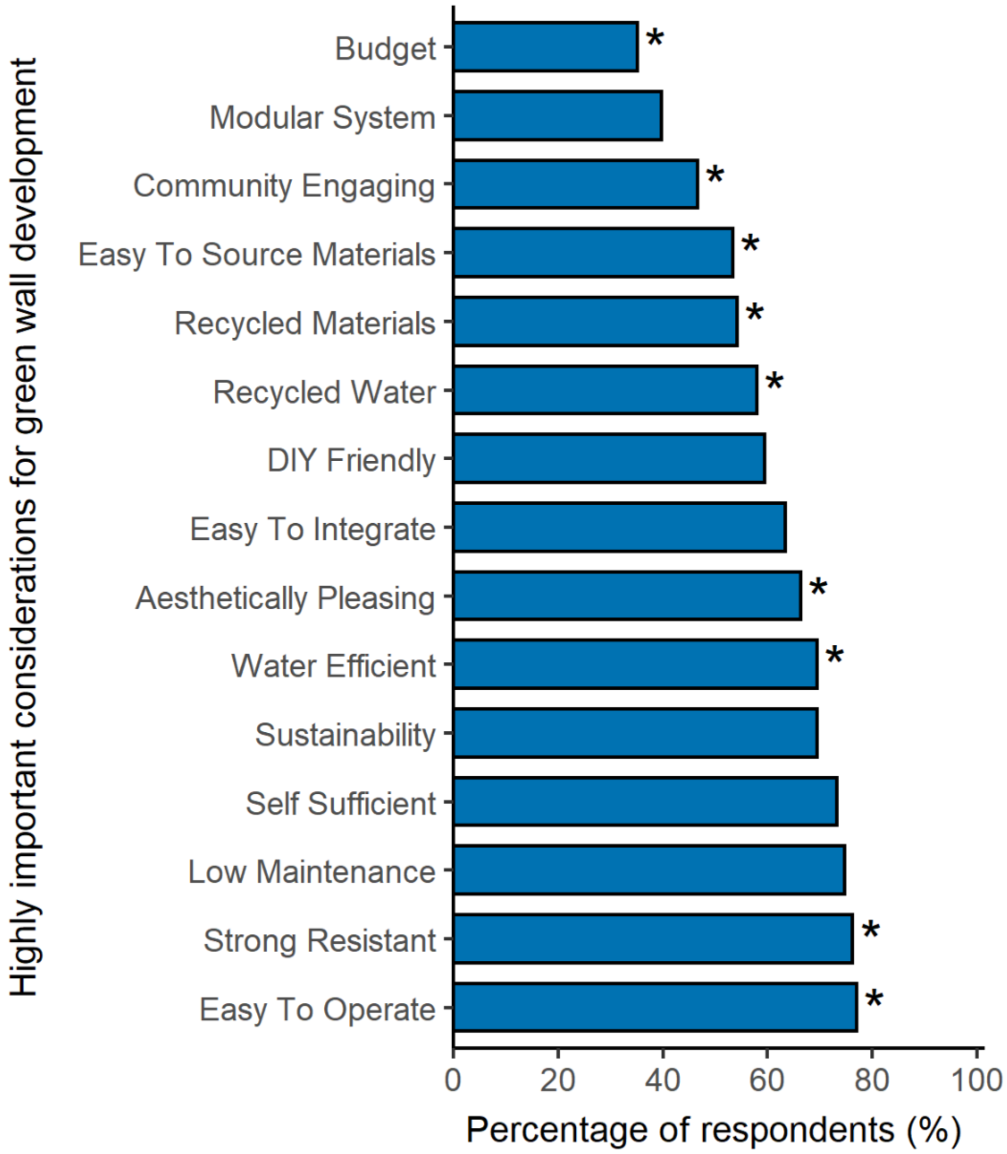

Figure 5.6. Distribution of respondents who reported each consideration as highly important for local green wall development (n = 131). Asterisk denotes significant Pearson Chi-square tests of independence with Monte Carlo simulations (B = 1000) across at least one demographic criteria.

There was an association between the participants' income bracket and their ranking of three considerations for GW development. Participants with low income ranked budget as a highly important consideration more frequently than the middle, high- and higher-income brackets (70.0% vs 31.8%, 25.7%

and 16.7%, p = 0.001). Participants earning a high income considered ease of operation as a key priority for GW development significantly more so than those earning a low-middle income, who perceived it as a moderate-high priority, and those earning a higher income considered it a relatively low priority (91.4 vs 72.7-75.0 and 33.3 %, p = 0.003). Participants earning a high income also considered structural integrity and weather resistance as a high priority for GW development, which was significantly greater than low, middle and higher-income brackets (91.4 vs 75.0, 61.4 and 66.7 %, p = 0.032).

Participants' Accessibility/Remoteness Index (ARIA) was associated with their ranking of several considerations for GW development; respondents who reside in Outer Regional and Remote Australia ranked community engagement as highly important, significantly more so than those from a Major City or Inner Regional region (76.9 and 60.0 vs 43.2 and 38.9 %, p = 0.018). Respondents who reside in Outer Regional Australia ranked easy to source materials as a highly important consideration significantly less than Major City, Inner Regional and Remote regions (38.5 vs 55.8, 50.0 and 60.0, p = 0.049). Respondents residing in a Major City were more likely to rank using recycled water as a highly important consideration than those from Inner Regional, Outer Regional and Remote regions (62.1 vs 50.0, 46.2 and 40.0 %, p = 0.009). Additionally, respondents residing in a Major City or Remote region ranked being water efficient as a highly important consideration more frequently than Inner and Outer Regional regions (75.8 and 80.0 vs 46.2 and 50.0 %, p = 0.002).

Discussion

1. Green Wall Awareness, Experience and Perception

This exploratory study highlights the potential desire for greener cities in Australia, with almost all participants expressing that they wished that Australia followed the lead of other, greener nations. With only ~17% of respondents spending significant time near a green wall at their place of work, study or residence, most participants nonetheless perceived them positively due to benefits including improved air quality, beauty and aesthetics, and reducing the urban heat island effect. These perceptions have been commonly identified in previous studies, where greenery is shown to improve positive associations with an area by counterbalancing urban stressors, and providing perceived improvements to air quality and aesthetics among two of the most commonly recognised benefits [331-333].

This positive association with mental health is further supported by ~ 70% of the 263 reviewed studies by Wendelboe-Nelson, *et al.* (2019) that have been shown to fulfil these basic societal needs by evoking positive emotional and restorative responses [298]. This agrees with the outcomes of the present study, where most respondents reported that having a green wall at their residence would likely improve their quality of life, either through the aforementioned benefits or by facilitating positive emotional and restorative responses when in the vicinity. The most frequently reported emotional positive responses in this study were related to feeling more at peace and having a stronger sense of community pride and belonging. These responses also align with the studies that have implicated GI as a means to improve quality of life, where a number of surveys have shown a shift in the public's perception of local area characteristics such as functionality and ability to conserve local biodiversity [334].

The participants' demographic characteristics correlated with their awareness, experience, and perception of green walls in this study. Females tended to have greater green wall awareness and recorded perceived aesthetics/beauty and community pride as highly important benefits more so than males. This preference has been attributed to gender-based differences in leisure time [278], and also a greater concern for "protecting the earth" than males [335]. However, this finding is not consistent across all previous studies

[336], and the reason for the observed gender bias observed here could not be deduced.

In contrast, age in the current study had no association with awareness of the perceived benefits of GWs. This is a novel finding, as age is often found to be an influencing factor on the perception of GI, where age tends to have a positive association with positive perceptions [307, 319]. This could be due to older individuals having greater life experience and knowledge, which impacts their view of GI [337, 338].

In this preliminary study, education was not found to have a relationship with an individual's awareness, experience, or perceptions of GWs. This finding counters the general trend from previous work, where the level of education has been generally found to be positively associated with a greater level of environmental understanding, perception, and knowledge, as well as a heightened sense of environmental awareness [307, 337, 339, 340]. Typically, higher levels of education have been found to increase an individual's awareness of both the benefits and consequences of environmental issues and can also result in higher levels of environmental responsibility [337, 339, 340]. This is likely a result of aspects of higher education informing individuals of the benefits and costs of various types of greenery, which in turn encourages educated individuals becoming involved with its strategic development - for instance, Gashu *et al.* (2019) demonstrated that individuals with tertiary education were more willing to participate in GI development than those that had received less education. However, in the current study, participants across varying levels of education were similarly informed. This is likely due to a lack of relevant GI education in tertiary programs in Australia, however further studies will be required to validate this theory.

Interestingly, locational preference differed across age and geographic groups, with young-middle aged respondents reporting that they would prefer green wall development in their place of study/work. In contrast, elderly respondents preferred their place of residence. It is possible that this reflected the respondents' primary occupation, with younger respondents more likely to be involved in study or employment. Participants residing outside of Australia's Major Cities tended to report a preference for development in their place of study/work, whereas city dwellers had split preference between their place of study/work and their residence, once again possibly reflecting employment status. The differences between the age groups and locational preferences could also be related to property ownership. As property ownership increases with age, and the installation of green infrastructure may prove problematic when renting a residential dwelling [331, 341-344]. Thus, older participants indicated a preference for residential-level GI in this study.

Furthermore, as home ownership is becoming less obtainable as the cost of living increases, this could act as an increasingly significant barrier to green wall implementation, particularly if landlords and tenants do not agree on the implementation of green infrastructure such as green walls [342]. Home ownership and rental properties complicate the green wall uptake. GW implementation has the potential to increase rental income and perceived property value. However, GWs can also increase maintenance costs to the respective property owners and create a burden of responsibility for both the landlord and tenants, which is often seen as a negative [345]. Furthermore, the environmental priorities between landlord and tenants may not align which could prevent uptake [345].

Young participants also perceived stormwater management as a highly important benefit, more so than older age brackets, and experienced feeling peaceful when in the vicinity of a green wall more frequently. The importance placed on stormwater management is matched in other studies both for residents and employees. A study by Derkzen *et al.* (2017) identified stormwater management as the second-ranked service provided by GWs, while Keeley *et al.* (2013) revealed a desire to incorporate GI solutions by younger staff employed in stormwater management [343, 346]. Additionally, low-median income earners recognised increased biodiversity as a highly important benefit, more so than higher-income earners. The importance of increased biodiversity and the need to conserve nature in urban environments through the use of GI has also been recognised in other studies [341]. The income-linked trend detected in the current study could be a result of younger people, often lower-income earners, having a greater environmental consciousness and preparedness to commit to increasing GI [347].

Respondents residing in a Major City liked green wall feature(s) more so than those from the other regions, while residents of Remote regions experienced a greater sense of community belonging when in the vicinity of GW. Similarly, Hinds and Sparks (2008) found people who grow up in remote regions exhibited a greater emotional affinity toward the natural environment compared to urban dwellers [348], which could account for the greater sense of belonging connected with GI and a greater desire to green the surrounding areas [349]. Urban dwellers' greater appreciation of green wall features could be explained by those residing in densely populated areas tending to value GI to a greater extent [350]. In more densely populated areas, people tend to pay a higher price for GI despite being smaller in size or area, most likely due to low GI accessibility and scant existing levels of green coverage [342]. However, this could be driven by an underlying cultural difference between those who work and reside in urban areas compared to remote regions. While ~97% of participants reported a desire for more green walls in the area they work, study, or live in, those who reported dislike for any green wall feature(s) showed no demographical inclination.

Interestingly, there were no patterns associated with feeling safer in the presence of a GW identified in the current study, in contrast with previous findings, with GI generally found to be associated with a sense of safety [307, 351]. Furthermore, the quality of green spaces has also been found to influence the perception of safety in other studies, which increases if green spaces are well maintained, and decreases in unmaintained locations [307, 351]. Also, the greening of unsavoury, dilapidated or vacant areas has been shown to improve people's sense of safety in an area while also decreasing crime [352].

2. Willingness to Pay for Local Green Wall Development

Most participants reported that they were willing to pay (WTP) to construct a green wall at or near their residence; however, the amount they were willing to invest varied with their income. Interestingly, those earning a median to high salary were most likely to invest the highest threshold of >$800 AUD into green wall construction, and those in the highest income bracket were the least likely to invest at this threshold (0% of respondents). This contrasts the widespread theory that WTP is a product of income, as has been shown in previous studies where buyers with a higher socio-economic status tend to be more willing to invest financially in green attributes for their residence [347, 353]. For example, Hu *et al.* (2014) clearly demonstrate that only relatively wealthy homebuyers were willing to invest in green attributes when in the market for apartments in Nanjing, China [353]. Contrastingly, the current study demonstrates that income may not be the primary determinant for financial investment in GI, and there is a potential for other factors, such as property type or ownership, to also affect WTP.

Interestingly, these findings support those of several other studies, where younger participants have been shown to be more willing to pay for GI and green development than older participants [334, 347]. Mell *et al.* (2016) demonstrated that WTP is also influenced by aesthetics, where the degree of attractiveness of green space was positively correlated with WTP. However, the authors acknowledged that income was a key barrier to GI implementation [334]. This relationship also could be driven by the respondents' level of connectedness to nature. Lo and Jim (2010) believed that WTP could be driven by youth having a greater environmental consciousness, equating to a greater commitment to GI, while other studies have found that exposure to the environment and environmental concerns during childhood and a stronger interaction with nature could have established a stronger will to conserve the natural environment in the younger generations [348, 354, 355].

Surprisingly, the current study found no relationship between willingness to pay and location (Figure 5.2). This contrasts with the commonly detected trend that people in urban areas value GI, such as GWs, to a greater extent [356]. This frequently published trend could be associated with multiple factors. A greater WTP could be driven by the likelihood of urban areas tending to have better employment opportunities, work conditions and higher incomes, resulting in individuals having a greater availability to invest in GI [356]. Furthermore, GI is often valued more highly in urban spaces, possibly due to the lack of green space coverage and accessibility in urban environments [342]. Similarly, in low density urban areas, the accessibility to GI is relatively higher, and thus, GI valuation is lower [342]. The factors driving the results for the current study could be related to the majority of participants having some form of basic awareness of GWs or that most did not live or work near a GW (83.2%), which was consistent across all demographics, including locational remoteness (Figure 5.2). However, this may need to be investigated further in order to elucidate this trend.

3. Potential Barriers to Local Green Wall Development

Personal budgetary limitations were the most reported reason for not selecting a higher threshold for WTP for local green wall construction. This finding is interesting, given the aforementioned income differences across participants and their WTP. These differences may be explained by the other reported motivations, including uncertainty around construction requirements, material costs, appropriateness for the residence, or simply that the threshold selected was considered by the respondent to be reasonable for what they consider a GW to be worth.

However, participants were more willing to invest if the local council or government assisted with construction, where assistance through guidance, workshops and technical support were among the primary services requested. The influence of local government policies, guidelines and support has been proven to increase green infrastructure, such as green walls, in Australia's cities as councils that had GW policies and guidance tended to have more green wall projects than those which have no such policies in place [34, 357, 358]. Fiscal services were identified as a secondary form of required assistance, where participants reported that they would be more willing to invest in local green wall development if they were provided with rebates, funding or incentives. These barriers have been commonly found amongst previous studies, where studies have frequently recommended the use of education programs, technical support, and financial incentives to increase GI development on private properties [34, 284, 293, 359, 360]. Fortunately, technical guidelines for local GI development are now available through a growing number of councils, such as the Inner West Council in Sydney, Australia, which details aspects such as the design process, site selection, construction and maintenance [361]. Additionally, the government is not the only current source of technical guidelines for GI in Australia, with initiatives such as the “It’s Time to Grow Up” eBook developed by university scientists also publicly available [362]. Future work should determine whether these resources are utilised effectively by the Australian public, particularly given that this was identified as a key barrier to local GW implementation in the current study.

In an attempt to understand what considerations were the most important for local GW development and to identify potential barriers for implementation (if considerations were not met), the current study found that ease of operation, structural durability, and maintenance were the most important factors identified by participants when considering building a GW. This finding aligns with other studies as functional aspects, such as structural/installation issues, and maintenance regimes, have been commonly viewed as negative issues associated with GW implementation [331, 334, 341, 343].

These factors were thus investigated in greater detail. Considerations varied substantially across all demographics except education. Female participants tended to prioritise budget, community engagement, recycled materials, recycled water, and water efficiency significantly more so than males. At current, there is sparse literature related to this topic, though the current results align with findings from other industries. Previous research shows that females are generally more environmentally conscientious than males, and tend to commit to and maintain environmentally-friendly habitats, such as recycling, more so than their male counterparts [363-365]. Additionally, females are more conscientious about water conservation [365], which aligns with the tendency of females to be more concerned about the use of recycled water and water efficiency in the current survey.

Elderly participants prioritised aesthetics when considering building a GW more so than younger participants. This aligns with previous studies, where older age groups tend to prioritise the aesthetic value of green spaces in urban areas more so than their younger counterparts [319]. People, in general, have been shown to prefer more natural environments compared to constructed urban environments and find greened buildings more aesthetically pleasing than those that do not possess GI [269, 331].

Participants earning a high income considered ease of operation and structural integrity more important than the other income brackets, and those earning a low income, unsurprisingly, prioritised budget. The budgetary limitations associated with income is frequently cited as a concern or consideration for GW construction, while those with higher incomes can afford to consider other requirements [334, 342]. There is sparse literature available detailing the differences in priorities for GW development across income brackets.

Participants residing in Major Cities prioritised recycled water and water efficiency more so than the outer regions, whereas participants residing in Remote Regions prioritised community engagement and water efficiency, and those residing in Outer Regional areas prioritised community engagement and considered ease of sourcing materials as less important compared to other regions. With climate change increasing the uncertainty of water availability globally, it is understandable that many participants across Australia, a drought-prone country that often experiences water shortages, considered water consumption and efficiency was an important factor when building a GW [342, 343, 366]. The increased likelihood of water scarcity and extreme droughts is an important issue, particularly in drought prone areas, as GWs can consume large volumes of water depending on the temperature, humidity, solar exposures, air flow of the area and the vegetation and substrate type of the GW [366, 367]. This may be managed through appropriate plant species selection and the addition of water storage and recycling infrastructure [366, 367]. Green spaces are often a place of social interaction, which may explain why it is so highly prioritised by those in remote and outer regional areas, being regions of lower population densities. Thus, greenery even in the form of a GW may be associated with greater community engagement which is prioritised due to its positive effect on mental health and wellbeing [351]. However further investigation is required to confirm why community engagement is a high priority for these ARIA groups.

Despite the benefits of this method, the potential limitations should be acknowledged [368]. The survey distribution methods may have reduced the representativeness of this exploratory study; thus, the generalisability of the current findings is reduced, and care should be placed on the conclusions. This was, however, an exploratory study exploring an entirely novel area of Australian green wall research, and there is great potential to build upon these findings with a larger sampling pool. Limitations associated with surveying can include non-response bias and in-sample selection bias, particularly as this was a voluntary survey that may have resulted in an overrepresentation of certain socio-demographic profiles [369]. Additionally, placing a heavy cognitive burden on the participants could also act as a limitation when engaging with the survey and survey fatigue could occur if more questions were included [370, 371], and there is a potential risk where the WTP responses are in relation to moral satisfaction of addressing a greater social issue at hand and contributing to common goods as opposed to the actual economic values for these goods [372]. Nevertheless, additional survey mechanics could be incorporated to improve any adaptation or methodological development and reduce any potential limitations. Furthermore, the literature recognises the stated preference survey method as the most appropriate method when investigating the non-market benefits or value of a specific good, such as green walls [373-375]. Additionally, further replication of this study could enhance its trustworthiness and help identify trends and patterns within the Australian population.

Future work aiming to understand public perceptions of GI, both in Australia and internationally, may utilise methodology similar to this study to identify barriers to implementation as well as demographic associations amongst the general public. The survey design used here could be adapted to suit any nation’s pursuit of understanding public perceptions through the use of the lowest tier of government/administrative boundary, and this form of analysis facilitates robust conclusions and provides statistical significance on its outcomes relating to demographic differences. While this study identified several novel trends in Australia, future work should aim to collect a larger sample size to gain further insight into these trends.

Recommendations and conclusion

While the consensus amongst the Australian community was found to be positive with respect to green wall awareness, experiences and perception, there was a demand for greater educational, technical and fiscal support from different levels of governments and businesses to provide the necessary resources for local green wall development. These demands are often seen as barriers, but when they are overcome, there is a marked increase in the implementation of GI. This is supported by Irga *et al.* (2017), who demonstrated the impact of education and informational support, as Australian local governments that provided this kind of support tended to have a greater number of green wall installations.

In Australia, these demands are beginning to be addressed, although the rate of change is slow and more can be done [34, 357, 358]. The internationally proven methods demonstrate that various support approaches increase GI implementation, whether it be through education, policy, resource or fiscal support [34, 357, 358]. Furthering the educational resources, policy development, technical support, and fiscal support would result in a greater uptake of GW implementation, and Australia may be able to follow the example set by green countries such as Singapore, Germany and Canada. While this exploratory study identified which groups are likely to be the most receptive to the promotion of green initiatives and specific details related to which aspects of GI have the greatest appeal, it has also highlighted what potential groups may need extra support to implement green infrastructure projects. Additionally, it has outlined the potential barriers across the different demographics and how these barriers could differ over an individual's lifetime. Examples of how this research could be capitalised on would include the development of support programs that encourage the development of non-permanent green walls that require minimal maintenance for owners and tenants. Other approaches could be targeted at encouraging men to engage with more green initiatives including GW implementation. This information should be of value to governments when developing and tailoring their support programs.

Appendix

Table 5.3. The Australia-wide survey that was distributed to 397 local government and voluntary councils and listed in two council e-newsletters.

Is this the first time you have heard of green walls?	Yes
	No
Which level of awareness best describes your understanding of green walls?	No awareness of green walls prior to this survey
	Seen or read something about green walls
	General understanding of green walls
	Strong interest in green walls
	Working in an area involving or related to green walls
What comes to mind/how do you feel when you see or walk past a green wall?	Open-Ended Response
Do you live near or work near a green wall?	Yes
	No
Were there any features that you liked on any of the green walls you have seen?	Yes
	No
If yes, then what were they or how would you describe them?	Open-Ended Response
Were there any features that you disliked on any of the green walls you have seen?	Yes
	No

If yes, then what were they or how would you describe them? And how would you change them?	Open-Ended Response
What do you think are the three main benefits of a green wall?	Open-Ended Response
What are the benefits of green walls that are most important to you? Please select up to five benefits you believe are the most important.	Improved Air Quality
	Beauty and Aesthetics
	Increased Biodiversity
	Improved Health
	Insulation for Buildings
	Noise Reduction
	Urban Heat Island Effect
	Stormwater Management
Would you like to see more green walls in the area you work/study or live?	Yes
	No
Where would you like to see more green walls, in the area where you live, or around your place of work/study?	Live (near my home)
	Work/study (near my work or educational institution)
What is the main reason for your answer above: how would more green walls improve the location you named?	Open-Ended Response
If your place of work/local council encouraged/assisted with the construction of a local green wall, would you consider constructing your own green wall?	Open-Ended Response

What type of assistance, if any, from your local government or employer do you think should be provided to people to encourage them to build their own green walls?	Open-Ended Response
What discourages you from constructing your own green wall?	Open-Ended Response
What would you be willing to spend into order to construct 3m x 3m green wall at/near your property?	$0
	$1 - 200
	$201 - 400
	$401 - 600
	$601 - 800
	$801 - 1,000
	$1,000+
Why did you select that answer?	Open-Ended Response
Do you believe having a green wall in/on your property would improve your quality of life in one way or another?	Open-Ended Response
Do you think that if your house had a large green wall on it, it would improve your time at home? Why?	Open-Ended Response
What is your gender?	Male
	Female
	Other/prefer not to disclose
How old are you?	Under 18
	18 – 25
	26 – 35

	36 – 45
	46 – 55
	56 – 65
	66 – 75
	76 +
	Prefer not to disclose
What postcode do you live in? If you prefer not to disclose then please enter 0.	Postcode
What is your ancestry?	Open-Ended Response
What is your highest level of education?	High School graduate
	Bachelor's degree
	Graduate Diploma or Certificate
	Master's degree
	Doctoral degree
	Other
What is your annual income bracket?	$0 – $40,000
	$40,001 – $80,000
	$80,001 – $120,000
	$120,001 – $160,000
	$160,001 – $200,000
	$200,001 +
	Prefer not to disclose
What is the main language spoken in your home?	Open-Ended Response

Do you know of other green cities across the world?	Open-Ended Response
Which country do you think has the 'greenest' cities?	Open-Ended Response
Do you wish Australian cities followed the lead of some other countries and became greener through green wall installations?	Yes
	No
If so, which city(s) would you follow to increase greenery in Australian cities?	Open-Ended Response
Are you more likely to feel any different when you are in an area with a green wall?	Yes
	No
If yes, then how so? Please tick the following:	Safer?
	More sociable?
	More at peace?
	A stronger sense of community pride?
	A stronger sense of belonging to your community?
	Other (please specify)
What information do you think is important to know before designing and constructing a green wall?	Open-Ended Response
If you were to develop a community centred green wall, to what extent are the following considerations important to you	Budget friendly (less than $100)
	DIY Friendly
	Easy to integrate onto the wall

and/or the community? On a scale from 1 (not important) to 5 (very important).	Low maintenance
	Easy to operate (drainage, maintenance and irrigation system)
	Self-sufficient drainage and irrigation system
	Community engaging
	Aesthetically pleasing
	Easy to source materials
	Made of recycled materials
	Use recycled water as its primary water supply
	Sustainability
	Water Efficient
	Modular system enabling versatility to scale up
	Structurally strong and weather resistant
Is there anything you would like to add regarding green walls?	Open-Ended Response
If you wish to enter your details for your chance to win a $100 Bunnings voucher or receive a notification when the Australia wide Community Green Wall Guide is finished then please provide the following:	Name
	City/Town
	State/Province
	ZIP/Postal Code
	Email Address

6. Evaluating And Comparing The Green Wall Retrofit Suitability Across Major Australian Cities

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Keywords

Greenwall retrofit; Vertical greenery system; Green walls; Green infrastructure; Sustainability; Urban forestry

Abstract

Urban densification continues to present a unique set of economic and environmental challenges. A growing shortage of green space and infrastructure is intrinsically linked with urban growth and development. With this comes the loss of ecosystem services such as urban heat island effects, reduction of air quality and biodiversity loss. Vertical greenery systems (VGS)

offer an adaptive solution to space-constrained areas that are characteristic of dense urban areas, and can potentially improve the sustainability of cities. However, in order to promote VGS uptake, methods are required to enable systematic appraisal of whether existing walls can be retrofitted with VGS. Further, feasibility studies that quantify the potential for retrofit suitability of VGS across entire urban areas are lacking. This study established an evaluation tool for green wall constructability in urban areas and validated the assessment tool by determining the quantity of walls in five major Australian cities that could potentially have VGS incorporated into the existing infrastructure. Each wall was analysed using an exclusionary set of criteria that evaluated and ranked a wall based on its suitability to VGS implementation. Sydney and Brisbane recorded the greatest proportional length of walls suitable for VGS, with 33.74% and 34.12% respectively. Conversely, Perth's urban centre was the least feasible site in which to incorporate VGS, with over 97% of surveyed walls excluded, mainly due to the prevalence of <1 m high fence lines and glazed shopfronts. This study aimed to evaluate feasibility assessments of green wall retrofitability in highly urbanised areas with the intention of creating an analytical method that is accessible to all. This method, coupled with the promising number of feasible walls found in this study, emphasises the need for more government policy and incentives encouraging green wall uptake and could play a pivotal role in the expansion of green infrastructure and urban forestry.

Introduction

Inherently, the urbanisation process is reliant upon the alteration, destruction or degradation of the natural environment [376]. Further, the reduction or removal of vegetation is rarely compensated or offset within developing cityscapes [377]. Incorporating green spaces and vegetation into highly urbanised areas has become challenging as population growth increases, cityscapes densify, and competition for space/land intensifies [59, 378, 379]; Though when incorporated, urban forestry to has been documented to improve the urban environment, particularly in the United States, Canada and Europe [58, 89, 93, 99, 102, 120, 380, 381]. Interestingly and despite the different locations globally, all cities experienced similarly positive outcomes when all types of urban forestry were increased [51, 58, 88-90, 97, 99, 102, 105, 120, 130-133, 136, 380, 382-384].

Vertical greenery systems (VGS) presented as an innovative and adaptive solution, enabling the reincorporation of vegetation in cities while minimising the competition for space/land allocation in an urban setting [377, 378]. Taking advantage of new or existing walls and the external sides of buildings in urban areas provides considerable potential for the construction of VGS on pre-existing structures, thus aiding in the amelioration of the problems facing cities with limited greenery [377, 378]. VGS may assist with biodiversity and conservation [288, 290, 385], while also helping to integrate climate change resilience with increasing vegetation showing potential to sequester carbon dioxide, and enhance air quality [291-293, 386]. VGS have also been noted for their thermal insulation properties [387, 388], their ability to decrease the urban heat island effect, and their subsequent impact on reducing buildings' energy consumption [13, 279, 282, 283]. Additional benefits associated with VGS include reduced noise pollution [24, 156, 160, 290, 294], increased aesthetic value of urban areas [389, 390], and improved mental health and wellbeing of residences [295-298].

Through the retrofitting onto already built structures, VGS technologies have seen an expansion in Western Europe and North America [34]. Equally, the research, modelling, and case studies focused on VGS implementation are predominantly from those regions [34, 322-324]. This reliance on data and research from the Northern Hemisphere can act as a barrier when applying it to environments in the Southern Hemisphere, such as Australia, due to significant differences in vegetation, rainfall and weather patterns, temperatures, particularly when addressing the success of green wall projects [323, 324].

Subsequently, Australia has been slow to take up these technologies compared to other countries [33]. Locally, council policy on green infrastructure was seen to be instrumental in encouraging the implementation of green space projects, but the development of such policies is in nascent stages [34]. This indicates that government incentives, guides or policies could play a pivotal role in the expansion of green infrastructure, especially in dense urban areas where its benefits will be most pronounced [34]. Additionally, the global development of evaluation tools that can assist urban planners on a cityscape without being resource-intensive is lacking. Particularly, as most that provide a preliminary assessment of areas suitable for greening require a great deal of training, resources, funding or skills in the realm of remote sensing, and could act as a potential barrier to VGS implementation.

An important requirement to facilitate the initiation of the widespread adoption of green wall technology is investigations into determining the feasibility of VGS implementation for a given space. Feasibility studies inform policymakers, stakeholders and community groups of the potential for a city to take up green wall technology. Whilst green roof retrofitting studies have been undertaken in Australia [391], there is a general lack of equivalent studies aimed at analysing the potential of retrofit suitability for green walls [379]. This study aims to address the lack of feasibility assessments for green walls in three main stages, using major Australian cities as a model for this evaluation tool. Easily employed assessment criteria for green wall retrofit wall appraisal were developed to realise the technical transformation from qualitative judgement to quantitative evaluation. The appraisal tool was then tested and validated within five major Australian cities; Sydney, Melbourne, Brisbane, Perth and Adelaide. The results were then mapped and comparisons made between and within each city to further present the different levels of retrofit suitability of these areas.

Methodology

1. Wall Assessment

A green wall refers to vegetation that is grown vertically, often on a building's façade [392]. Types of green wall systems available range from simple direct green façades to more complex modular systems [281, 378, 393]. *Direct green façades* generally use climbing plants, which can be planted directly into the ground or in planters at various heights. For these systems, plants climb up a wall façade or cascade down. *Indirect green façades* are where climbing plants are guided by a trellis, cables or mesh, with a gap between the supporting structure and the building wall [378, 393]. *Living wall systems* can be complex, modular systems with a planting substrate that allows for a greater range of species to grow, but require a more complex setup with an irrigation system and more maintenance. They can also be hydroponic, where a material, such as felt, coconut husk or soil is used, and nutrients are fed to the plants via the irrigation system [378].

To determine the green wall retrofit suitability of existing walls in metropolitan areas, a rating tool was developed. The rating tool was designed primarily for green façade VGS, because of their simplicity in design and comparatively lower structural requirements than other VGS classifications. Further, green façades are relatively low cost and easy to maintain compared to pre-vegetated, modular living walls.

The wall dimensions required for inclusion in the rating tool was a height of greater than 1 meter. If the wall exceeded 3 meters in height, only the wall area from the immediate ground level up to 3 meters in height was assessed.

This rating involved an initial exclusionary set of criteria to either eliminate the wall from, or include in, further analysis (Table 6.1). The elimination characteristics represent circumstances where retrofit suitability becomes non-viable due to structural or regulatory issues. Glazed façades, walls with no ground access and driveways/garage doors, are all structural barriers to VGS implementation. In Australia, heritage buildings require approval from the local council or equivalent for aesthetic modifications, which may not be forthcoming. Walls designated for art would also require further approval from local councils. The barriers these wall types present to possible VGS implementation mean they are less likely to be appropriate for this use and were thus eliminated from further consideration on the basis that additional administrative difficulties would be required for greening at these sites.

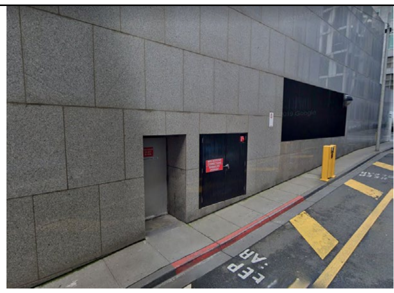
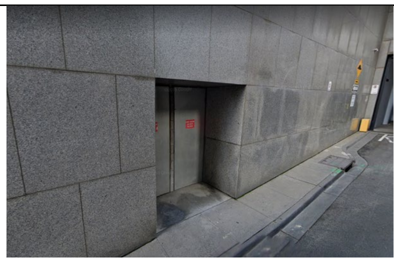
If an exclusion criterion was not triggered, each wall underwent an analysis through a series of six additional criteria (Table 6.2), resulting in a score between 0 and 6 that provided a representation of its suitability for green wall implementation. The criteria related to the wall's physical characteristics and its immediate surroundings and examples of each score are presented in Table 6.2.

Table 6.1 Characteristics that result in the exclusion of a wall from further analysis.

Elimination Characteristics
Glazed façades of 50% or more
Walls with no ground access (e.g. overhanging balcony or adjoining building)
Driveways/garage doors
Heritage listed front façades
Art (excluding 'tagging', but including street art)
Parks, playing fields and areas that do not have kerb side walls

Table 6.2. Set of criteria associated with a wall's immediate surroundings and physical characteristics to determine its green wall retrofit suitability. The

images are examples of each wall scoring taken from the survey area in Melbourne and represent retrofit suitability scores from 1 to 6. [394-399].

Questions	Score	Example
1. Does the wall have the capacity to have soil at its base?	a. Yes? +1 b. No? 0	
2. Is the wall next to a very narrow walkway or driveway?	a. Yes? 0 b. No? +1	
3. Can the wall have a drainage pipe at its base or can excess water flow into a nearby gutter?	a. Yes? +1 b. No? 0	
4. Is this wall in an area that is clearly used for storage of bins?	a. Yes? 0 b. No? +1	

5. Is there a fire exit on this wall?	a. Yes? 0 b. No? +1	
6. Does the wall have any services/service meters on it, or does the base of the wall have a service access point directly in front of it (e.g. firefighting equipment, electricity meters, and sewerage/pipe access or cable access)?	a. Yes? 0 b. No? +1	

2. Validation

To validate and test the rating tool, assessments were made within the five major cities in January 2020. The cities analysed were chosen due to their population size being greater than 1 million, and thus representing ‘major’ urban centres. A 4 km^2 area within each city was identified for this study that was centralised around the central business district (CBD). These locations were selected as they were generally the densest and most spatially constrained sites within the cities, and would therefore benefit the most from VGS implementation. Google Street View (Google LLC, 2020) was used to ‘walk’ through the sample area to analyse and assign a colour rating to all accessible walls within the study area. Walls and building surfaces with no street view available, and walls that already had green wall structures were given a separate rating. Walls scoring each rating were given a corresponding colour that was used to provide a representation of the retrofit suitability of green walls in each mapped area (Table 6.3). This was completed using Microsoft Publisher (Microsoft Corporation, 2019).

Table 6.3. Description of each rating and the colours prescribed to each rating after assessment.

Rating	Rating Description	Colour	Decimal Code (R, G, B)
Elimination	Excluded due to elimination criteria	Blue	0, 0, 255
0	Very limited retrofitability	Black	0, 0, 0
1	Moderately limited retrofitability	Red	194, 0, 0
2	Limited retrofitability	Orange	255, 128, 41
3	Moderate retrofitability	Yellow	240, 234, 0
4	Moderate retrofitability	Light Green	0, 255, 0
5	High retrofitability	Leaf Green	102, 153, 0
6	Excellent retrofitability	Deep Green	0, 102, 0
No Google Street View	Unable to be surveyed due to lack of Google Street View	Pink	255, 0, 255
Already Greened	Area of interest already had a vertical green wall	Purple	102, 0, 204

To compare the mapped areas from each city's urban centre, the length of the walls scoring each rating were measured using Google Maps Measuring Distance tool (Google LLC, 2020). Descriptive statistics were used to summarise the data and allow for comparisons, with spatial trends analysed to determine whether certain areas returned a higher percentage of walls more suitable for greening than others.

Results And Discussion

The results below show the feasibility of walls for green wall installation in five major cities CBDs (Table 6.4). Overall, most walls assessed that did not present an elimination characteristic, were most likely to be *high retrofitability* for green wall construction with a rating of 5 (Table 6.4). These walls accounted for on average 6.10% of the walls surveyed in each city. The next most common retrofitability scores for each city were in the *moderate retrofitability* range (score of 4), averaging 5.86% of the city walls, followed by walls scoring 3, averaging 3.53% of the city walls. Average feasibility scores representing limited green wall potential (scores 0-2), the most retrofitable walls (score 6) and already greened walls all contributed to less than 2% of the available walls across the five cities (Table 6.4). A general assessment of the spatial patterns from the five maps generated (Figures 6.1–6.5) also indicated that walls with lower scores (0–3) were found more frequently in narrow streets and shorter alleys. Existing greened walls did not demonstrate clear spatial trends in any city, due to the current low level of vertical greenspace used in Australia. A considerable proportion of streets within the sample areas could not be assessed due to the absence of Google Street View (5.40%). Walls scoring 0 for retrofitability were the least common wall type detected, contributing to <1% of the walls amongst the tested cities.

Table 6.4 Feasibility scores as percentage (%) breakdown of each Australian city, in descending order of city population. A higher rating indicates greater green wall retrofit suitability. Eliminated walls possessed characteristics preventing green wall installation.

Feasibility Score	Sydney	Melbourne	Brisbane	Perth	Adelaide
6	0.98	1.41	1.76	0.05	0.03
5	8.12	5.83	16.23	0.04	0.28
4	12.38	4.77	9.66	0.98	1.52
3	7.57	4.98	3.27	0.29	1.53

2	2.42	5.07	1.81	0	0.29
1	1.58	3.4	0.95	0	0.02
0	0.68	1.31	0.44	0	0
No Street View	9.35	6.75	4.9	1.29	4.68
Already Greened	0.36	0.34	0.16	0.01	0.28
Elimination	56.55	66.24	60.82	97.34	91.36

1. Sydney

Sydney's CBD was found to have a high greening potential, with both the fewest number of walls eliminated (56.55%), and the greatest proportion of highly rated walls amongst the tested cities. Highly retrofitable walls in Sydney equated to over 9% of the surveyed walls and also had the greatest length of moderately retrofitable walls, equalling approximately 20% of walls surveyed (Table 6.4). Sydney also has the second greatest length of walls with limited retrofitability (approximately 5%; Table 6.4). This is also the city with the highest incidence of already greened walls (Table 6.4). Retrofitable walls were more common in the east and south sides of the rated area of Sydney (Figure 6.1). This was due to these regions transitioning towards residential zones, which resulted in less eliminated walls due to shop fronts with glazed façades.

Figure 6.1. Feasibility map of Sydney CBD. A higher rating indicates greater green wall retrofit suitability. Eliminated walls possessed characteristics preventing green wall installation. Approximate area of interest highlighted in red underneath (ArcGIS version 10.6.1, ESRI Inc., Redlands, USA).

2. Melbourne

Melbourne was found to be the third most feasible city for green wall retrofitting, behind Sydney and Brisbane. Melbourne recorded the second highest suitability rating of 6 of all the cities (Table 6.4) and third highest for walls rated 4 and 5 on our retrofitability scale (Table 6.4). Conversely, Melbourne was also the city with the highest frequency of limited retrofitability ratings, with approximately 10% of walls rating 0, 1 or 2 (Table 6.4). Interestingly, Melbourne also had the second highest percentages of already greened walls (Table 6.4). The northern half of Melbourne CBD demonstrated a greater proportion of feasible walls, despite this region being less densely built (Figure 6.2). The greater proportion of highly rated walls within this part of the city may, as was the case with Sydney, have been due to the presence of more residential buildings. For Melbourne, this spatial pattern was also influenced by the southern half of the CBD including the Yarra River and park areas, with few walls present. Melbourne was found to have many laneways that received low scores due to a prevalence of narrow walkways, utilities, storage of bins and fire exits. Although the Melbourne laneway shown in Figure 6.6D was eliminated due to its street art, it exemplifies laneways with characteristics found throughout Melbourne that resulted in reduced suitability ratings.

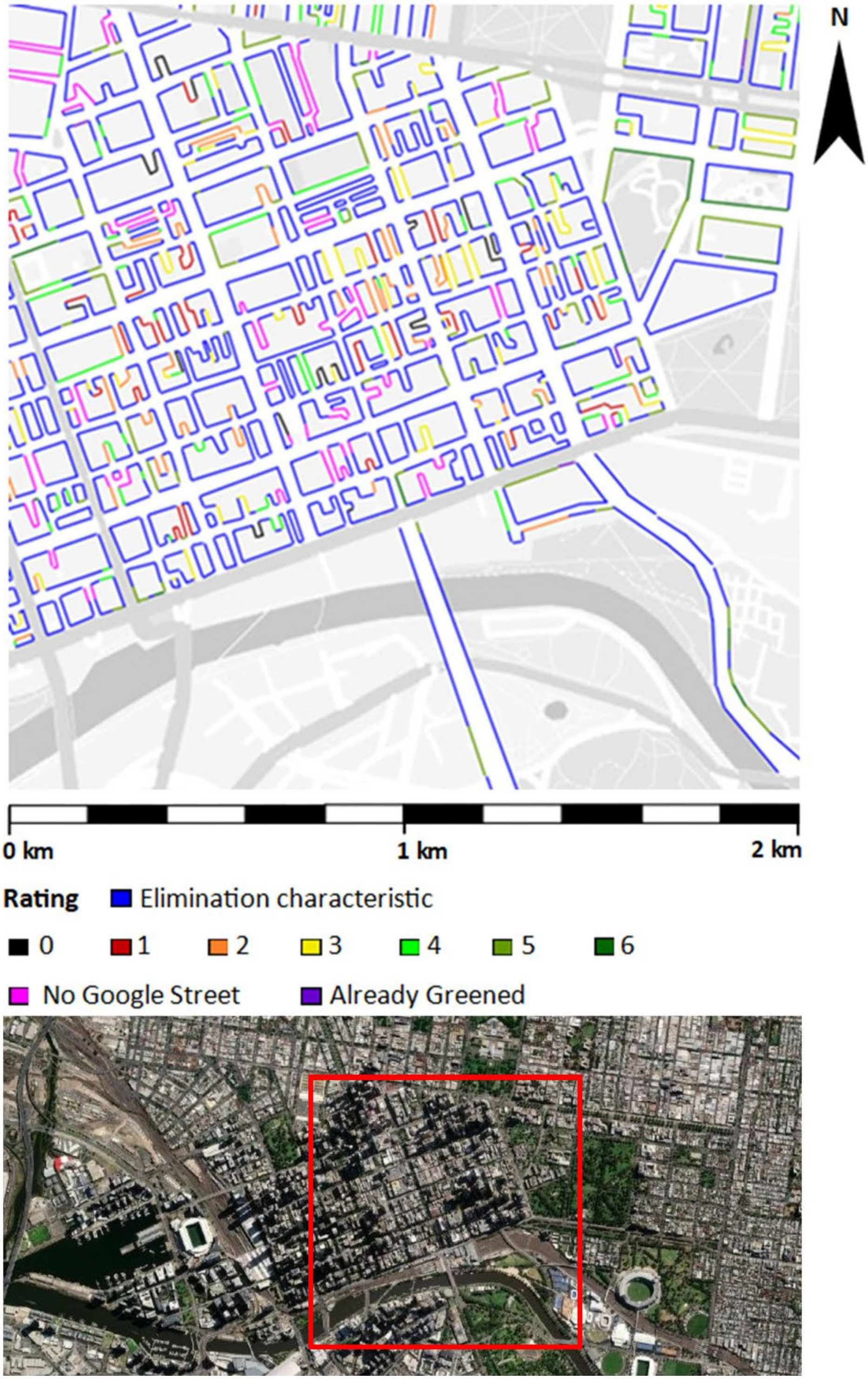


Figure 6.2. Feasibility map of Melbourne CBD. A higher rating indicates greater green wall retrofit suitability. Eliminated walls possessed characteristics preventing green wall installation. Approximate area of interest highlighted in red underneath (ArcGIS version 10.6.1, ESRI Inc., Redlands, USA).

3. Brisbane

Brisbane demonstrated a similar greening potential to Sydney as it had the greatest percentage of highly retrofitable walls, with almost of 18% of walls surveyed either rating 5 or 6 (Table 6.4), and the second lowest number of eliminated walls at just under 61% (Table 6.4). Despite having a high level of greening potential, Brisbane had the second lowest percentage of existing greened walls (Table 6.4). For Brisbane, the north-west region had the most walls with high green wall suitability ratings (Figure 6.3), partially due to more property boundaries made from brick with fewer utilities, resulting in higher ratings.

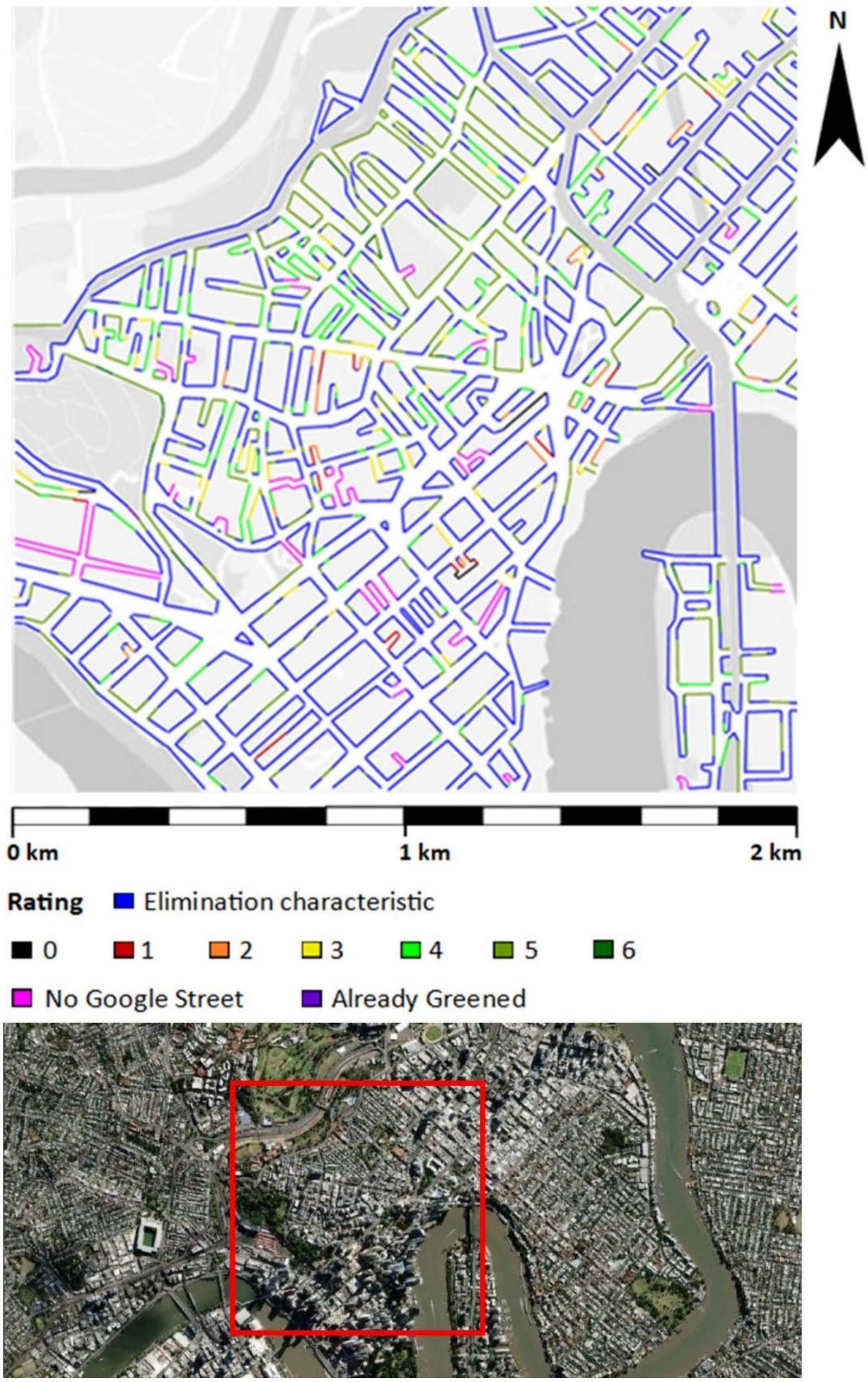


Figure 6.3. Feasibility map of Brisbane CBD. A higher rating indicates greater green wall retrofit suitability. Eliminated walls possessed characteristics preventing green wall installation. Approximate area of interest highlighted in red underneath (ArcGIS version 10.6.1, ESRI Inc., Redlands, USA).

4. Perth

Perth has the lowest percentage distance of potential green walls and the highest percentage of eliminated walls at 97.34% (Table 6.4). Interestingly, Perth also had no walls with limited retrofitability (Table 6.4). Perth's CBD was more spatially homogeneous than the other cities and lacked any clear l differentiation amongst local usage zones (Figure 6.4). Perth's study area included many shop fronts with glazed façades, contributing to the low green wall suitability. The residential property boundaries in Perth included more garage doors and fences less than one meter in height compared to the other cities studied, which further impacted Perth's percentage of feasible walls.

Figure 6.4. Feasibility map of Perth CBD. A higher rating indicates greater green wall retrofit suitability. Eliminated walls possessed characteristics preventing green wall installation. Approximate area of interest highlighted in red underneath (ArcGIS version 10.6.1, ESRI Inc., Redlands, USA).

5. Adelaide

Adelaide was similar to Perth, with the second lowest percentage distance of potential green walls with a total retrofitable percentage for all score of approximately 3.5%, and the second highest percentage of eliminated walls at 91.36% (Table 6.4). In contrast, Adelaide had the third highest percentage of existing green walls (Table 6.4). Green wall installation in Adelaide is limited largely due to glazed façades lining the streets of the CBD. Heritage buildings are also present in the centre of Adelaide, along with garage doors as the outermost boundary of many properties. Adelaide has more suitable walls for greening to the south and west sides of the city (Figure 6.5).

Figure 6.5. Feasibility map of Adelaide CBD. A higher rating indicates greater green wall retrofit suitability. Eliminated walls possessed characteristics preventing green wall installation. Approximate area of interest highlighted in red underneath (ArcGIS version 10.6.1, ESRI Inc., Redlands, USA).

6. General

The green wall feasibility rating tool developed to meet the aims of this study was tested and validated successfully, and could provide a general probabilistic tool for government and industry bodies seeking to increase the proportion of greenspace in their cities. It was found that green wall retrofitability differed among the metropolitan areas in Australia's cities. Greater than half of the walls in all cities demonstrated elimination characteristics, and were thus unlikely to be suitable for the construction of current, common green wall designs. Shop fronts with glazed façades (Figure 6.6A) were the main excluding factor, and was reflected in the spatial distributions as long stretches of eliminated walls through the centre of the CBDs dominated by commercial premises. Other buildings in the city areas also had glazed façades, for example the Adelaide Convention Centre has a 100-metre-long glazed façade [Figure 6.6B, [400].

Areas around the margins of city CBDs often transition towards residential development, and these areas regularly showed a growing proportion of feasible walls. This can be clearly seen in one of the study areas, Sydney (Figure 6.1), as the property boundaries of private houses in Surry Hills to the south and Kings Cross to the east displayed more greenable walls than the area to the west in Town Hall, where the streets were lined by more stores.

Several heritage buildings such as the Queen Victoria Building in Sydney (Figure 6.6C) were also found across the cities. The front façades of these buildings added to the proportion of eliminated walls. As cities expand from the centre outwards, more heritage-type buildings will become included in CBD areas. Heritage buildings have been identified for their lack in energy efficiency [401] and potential adaptive reuse to make cities more sustainable [402, 403]. Tassicker *et al.* (2016) suggests government policies should be improved to increase uptake of green infrastructure, including on heritage buildings. Wilkinson and Dixon (2016) state that building condition and structural capacity are major considerations for green roof retrofits of heritage buildings, factors that also apply to green wall retrofit [404].

In one of the study sites, Melbourne, there were noticeably more building façades with street art. This was due to the study area encompassing laneways that are famous for their painted walls, such as Melbourne's Hosier Lane [Figure 6.6D, [405, 406].

Figure 6.6. A. Glazed façades on shops fronts in William Street, Perth [407]. B. Adelaide Convention Centre, Adelaide [408]. C. Queen Victoria Building, Sydney [409]. D. Hosier Lane, Melbourne [410].

Previous studies have been conducted using GIS to map the feasibility of retrofitting green roofs in cities [411-414]. Mallinis *et al.* (2014) created a method using remote sensing and GIS to estimate the area which could be retrofitted with green roofs [415]. A study using geospatial analysis to map the feasibility of roofs for greening in a German city found that 14% of buildings were suitable [416], with significant feasible roof areas in inner city areas due to the high density of buildings in these areas. A similar case existed in the current work, with inner city areas with high building densities having higher probabilities of suitable walls being present. For example, south east Sydney (Figure 6.1) and north western Brisbane (Figure 6.3) are the areas of their respective cities with the highest density of walls, and had the greatest linear length of feasible walls within their study areas.

However, while building density can be an indicator of potential for greening, this is not always the case. Wilkinson and Reed (2009) found that only 15% of the buildings in the Melbourne CBD were suitable for green roof retrofit and suggested that there was a greater potential for green roof retrofitability in areas considered to be more residential, regional or suburban than the CBD [417]. This suggestion was supported by the current findings, as the northern half of the Melbourne CBD demonstrated a greater proportion of feasible walls, despite this region being less densely built (Figure 6.2), where the presence of residential buildings was greater and the presence of glazed façades, heritage buildings and other elimination characteristics was reduced. Additionally, this likely reflects the abundant narrow laneways in this city (Figure 6.2), with walls commonly eliminated due to safety concerns associated with implementing green walls, as well as their use as rubbish and bin storage areas, and difficulties associated with maintenance and light in these streets [418].

These observations notwithstanding, if inner-city laneways are not subject to elimination criteria then they can be considered urban canyons, which would benefit significantly from the implementation of green walls. These areas trap pollutants from traffic and often experience high air pollution levels [419] and while, many urban street canyons were encountered during the mapping process across all cities, many studies have found VGS to be an effective strategy to improve air quality in urban street canyons [292, 420, 421]. Though the key to their success is ensuring the plant species selected for the

VGSs are based on their tolerance to air pollutants [420] and light availabilities/requirements, most likely on a site-by-site basis. A follow up site inspection would assist in ensuring appropriate species were selected and the use of publicly available information from green guides, online databases, case studies, plant suppliers, and government bodies, would provide locally relevant information on appropriate species [362, 422-426].

A previous study in Melbourne CBD found that approximately 15% of buildings had the potential for green wall retrofitting [379], similar to the findings of the current study that found the proportion of walls with moderate and high retrofit suitability scores in Melbourne to be 16.99%. A recent study in Detroit, U.S.A., used six ecosystem services as criteria to map priority areas for green infrastructure [427], a spatial approach that could be strongly complimentary to the process used in the current study. The authors [427] suggested that after their model was used to identify priority areas where most benefits would be obtained from green infrastructure, a suitability assessment such as the one developed in the current study could be used for decision making at smaller spatial scales.

Many studies on green infrastructure relate to its thermal benefits [428], including decreasing the urban heat island effect, which especially impacts city centres [429]. Bartesaghi-Koc *et al.* (2019) proposed a classification scheme to determine the spatial arrangement of green infrastructure that would provide the optimal cooling effects, developed through mapping and classifying urban areas within Sydney using criteria such as daytime land surface temperature [430]. Razzaghmanesh *et al.* (2016) found green roofs have significant cooling effects on building temperatures in summer urban areas and could insulate heat in winter, and also suggested that green walls could be implemented to decrease the urban heat island effect in cities [431]. Another study also found a similar cooling effect from living walls [432]. Norton *et al.* (2015) also developed a framework to assess areas in Melbourne where the most benefit could be obtained from urban green infrastructure to reduce the urban heat island effect [433]. These studies thus show the cooling potential of VGS in cities, whilst the current study determined where they are feasible.

Research has been conducted on the ability of green infrastructure to contribute to urban wildlife corridors [434], an ecosystem service that is usually lost in urban areas. For example, Stenhouse (2004) found that areas closer to the CBD with a higher human population had a decreased vegetation connectivity [435]. Whilst VGS provide potential vegetated habitats, increases both to the size and prevalence of green walls would likely be necessary for them to have a measurable role in connecting habitat in urban areas [436]. A study on the extent of informal urban green space, such as railway corridors and vacant lots, in central Brisbane [437] found that 6.3% of the study area could be categorised as informal urban green space, and provided an important source of green space for conservation. The area identified by Rupprecht and Byrne (2014) was comparable to the size of feasible walls identified in the current study, with walls scoring 5 making up an average of 6.10% of the street side distances across each city. It is therefore probable that building walls in Australia’s city centres have the potential to provide some level of habitat connectivity and green space through green façade retrofitting, although there were notable spatial differences both amongst and within city CBDs.

The current findings could be influenced by government legislation or incentives related to green walls, as it has been previously demonstrated that relevant local government policies and regulations increase the number of green walls in an area [34]. Both the City of Sydney and City of Melbourne councils have policies regarding living walls and green roofs [438], and the City of Melbourne also has vertical greening initiatives [439], leading to these cities having the greatest proportion of existing greened walls, highlighting the positive impact of government initiatives. Currently, Perth has the lowest prevalence of green walls, thus the City of Perth aims to influence and assist its residents to develop an ‘urban forest’ which includes green walls to improve community health and recreation, and reduce the urban heat island effect [440].

However, despite the existence of incentives in some of the study areas, the prevalence of green walls in Australia is generally low, possibly a consequence of the lack of financial incentives to install green walls in Australia [33]. Costs have been identified as a major barrier to green wall construction [33]. On the other hand, it has been found that green walls in Canada increased property prices by 6 to 15% [438]. This, coupled with the promising number of feasible walls found in this study, emphasises the need for more government policy and incentives encouraging green wall uptake and the support from both globally and locally relevant research.

Limitations

While this study effectively developed an evaluation method for the retrofit suitability of green walls in urban areas, it does not take all factors into account. The structural capacity of each wall was not tested, and would require further assessment to ensure the suitability of individual sites. Each identified site would also require further evaluation to ensure the appropriate green wall construction type is selected as there are different typologies regarding green wall implementation. The determination would be centred around the suitability of either an extensive or intensive VGS, would result in different soil depths, plant types, substrates types, construction materials and soil compositions. Such an assessment must inevitably be made on an individual building basis. Building owner preference for green wall structures on their properties would also need to be determined on a case basis.

The method developed in this study thus provides a viable and accessible means for individuals, communities and organisations to determine the general retrofit suitability of an area of interest for green wall implementation.

This evaluation method was developed with simplicity in mind, to ensure it was accessible to all interested stakeholders, required little in terms of training or resources, and could be applied globally. Though, the proportion of suitable walls in any city is dynamic, particularly in areas undergoing rapid urbanisation, and will be subject to continual change due to construction of new buildings, so tool should be utilised as a preliminary assessment tool. In addition, this tool coupled with the presence of many new developments, like those seen in Perth [439], may lead to new greening opportunities emerging.

Conclusion And Future Directions

This study has aimed to contribute to the body of research regarding feasibility assessments of green wall retrofit suitability and retrofitability in areas of high urban density. The cities assessed were chosen for their relatively large population size, infrastructure generally suitable for analysis, global relevance, and the potential benefits obtained from greening. It was found that a large proportion of Sydney, Melbourne and Brisbane streets could support VGS projects. Spatial trends from the maps created reveal that in general, the highest probability of eliminated walls were on longer main roads through the centre of the CDBs. Adelaide and Perth did not return promising results for retrofit suitability of VGS projects, however these circumstances could change due to future infrastructure construction and expansion. Policy guidelines or incentives that encourage or require green initiatives in building requirements would undoubtedly provide more opportunities for VGS in these cities. Publicly available guides, based on scientific research, on sustainable green wall structures and species would also assist with increase VGS implementation.

The method of evaluation for this study was effective, with the exclusionary set of criteria removing subjectivity from the assessment. This method would be suitable for those looking to evaluate areas of interest and could be utilise by many stakeholders, from interested members of the public, to government organisation, as it is not resource intensive and does not require high levels of training. Furthermore, this tool could easily be utilised with readily available remote sensing techniques that are locally relevant to provide more detailed information and evaluation prior to site inspections. The evaluation tool's simplicity was designed with the intention of making an analytical method that is accessible to all within urbanised areas and enables comparison of the areas evaluated.

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7. Discussion

The application of urban forestry and urban greenery are promising solutions that could counterbalance the dynamic impacts of urbanisation. This multifaceted body of transdisciplinary work demonstrated this through the incorporation of a holistic approach by initially establishing a solid theoretical understanding of the impacts associated with urbanisation and their relationship with green implementation and urban forestry. Following that, this research progressed into the practical arena through the investigation of implementation and uptake barriers and the subsequent feasibility of urban greening installations and green goal targets. This was achieved by addressing the following research questions:

1. Investigate the relationship between air pollution and land use, land cover, and urban forestry to understand the potential associations between vegetation and air quality – Chapter 2

2. Investigate the effectiveness of vegetated green wall modules for noise pollution mitigation through sound absorption – Chapter 3

3. Investigate the impact of two significant events on outdoor ambient air pollution to elucidate dynamic factors affecting air pollution across a cityscape – Chapter 4

4. Investigate the social acceptability of green infrastructure, in particular green walls, by exploring the general public's awareness, experience, and perception of green walls, barriers to implementation, and willingness to pay for local green wall development – Chapter 5

5. Investigate the implementation and feasibility of green walls retrofitability in highly urbanised areas through the development of an analytical tool for preliminary assessment – Chapter 6

Theoretical Understanding And Investigation

The initial investigations elucidated and established the relationship between urban forestry and urban stressors such as air pollution and noise pollution. While the potential for air pollution removal by vegetation has been previously published, few studies investigated the associations between urban forestry and air pollution on a city scale, and the present research in Chapter 2 was the first to the author's knowledge to provide such an insight into the associations between vegetation and air pollution, while correcting for anthropogenic source, in order to quantify and evaluate the spatial variation of air pollutant concentrations associated with different forms of urban forestry. Incorporating anthropogenic pollutant sources and subsequent correction ensured that the hypothesis that urban forestry was associated with air pollution removal was explicitly tested. This novel approach addresses the spatial variability associated with distance from source present in extensive spatial studies but minimising the influence of distance from polluting source [81, 88, 89, 105].

This chapter established the initial theoretical foundation for this body of research. The associations between land uses such as transport, commercial, and industrial related activities, and high level of ambient air pollution were confirmed. Contrastingly, the significant association detected between parklands and low pollutant concentration demonstrated the impact of vegetation and its ability to influence air pollutant concentrations in an urban environment. Furthermore, this research found that different types of vegetation influenced air pollutants differently, with broadleaf evergreen forests tending to be associated with lower air pollutant concentrations.

Building on from that, this current body of research recognised the lack of studies associated with applied greenery as a noise pollution solution and aimed at addressing that by investigating the effective of planted modules for noise pollution mitigation through sound absorption (presented in Chapter 3). The outcome of this research highlighted the potential for vegetated green walls to play an important part in mitigating the impact of noise pollution, as the sound absorption coefficients of our planted green modules exceeded 0.5 for most frequencies, with one plant species reaching more than 0.9, consistently outperforming commonly used building materials and other vertical green systems, typically achieving a maximum sound absorption coefficient of 0.6 or less.

These findings underscore the potential of nature based solutions to play a significant role in mitigating the effects of urban pollutants such as noise and air pollution while simultaneously offering numerous positive impacts on our urban environments and their occupants.

However, these urban stressors do not occur in isolation. When addressing urbanisation and its negative impacts, spatial and temporal factors should always be considered. Thus, the effect of two significant events was investigated in Chapter 4 to elucidate the dynamic spatial and temporal factors that could affect air pollution across a cityscape. While the notion of spatio-temporal influences is not novel, the research's outcome was that the results demonstrated that both events, the Global Pandemic and Black Summer bushfires, had a significant impact on air quality. However, they impacted the air quality differently. Interestingly, this study showed significantly higher concentrations of PM_{10} during the bushfire period than during normal times, and significantly lower PM_{10} during COVID-19 restrictions. The inverse was found for NO_2, as there was significantly less ambient NO_2 during the bushfires and more during the COVID-19 period.

The unexpected findings highlighted the need for multifaceted policies and approaches when mitigating urban pollution, such as air pollution, particularly as these types of events will increase in frequency and severity. As urbanisation increases, the need for spatially interwoven and mutually supportive strategies and guidelines is vital.

Societal Considerations And Practical Applications

Once the negative impacts were elucidated and the need for diversified strategies was confirmed, the focus of this research shifted to exploring and understanding the societal considerations and practical applications required, which is critical if we wish to establish urban greening within Australian cities. Social acceptability, effective communication and wilful engagement bridges the gap between potential and actual implementation, particularly when integrating new or alternative solutions and technologies, such as green infrastructure or nature based solutions [302-306]. Social acceptance also helps reframe the potential barriers to implementation, particularly with financial or educational barriers [302-306], which is why it is essential to understand social acceptability around green infrastructure [307-309]. Thus, the social acceptability of green walls was investigated by exploring the general public's awareness, experience, and perception of green walls, barriers to implementation, and willingness to pay for local green wall development in Chapter 5.

While the consensus amongst the Australian community was found to be positive with respect to green wall awareness, experiences and perception, there was a demand for greater educational, technical and fiscal support from different levels of governments and businesses to provide the necessary resources for local green wall development. These demands are often seen as barriers, but when they are overcome, there is a marked increase in the implementation of GI. Interestingly, despite the perceived notion to the contrary, fiscal support and limitations were not the main driving factors for green wall implementation. This change could represent a shift in societal views about environmental stewardship or an increase in eco-anxiety as younger generations come to understand the environmental uncertainties they may face. The gradual loss of urban green spaces and the inaccessibility to large green spaces faced by some could also be driving the want for more urban forestry.

Furthermore, this exploratory study identified which groups are likely to be the most receptive to the promotion of green initiatives and specific details related to which aspects of GI have the greatest appeal; it has also highlighted what potential groups or influencing factors may need extra support or need to be addressed in order to increase the implementation of green infrastructure projects. The different categories of factors included institutional factors like level of awareness of GI and involvement in planning [284, 301, 307, 310-312]; socio-economic factors, including employment types, living arrangements or housing types/areas, income and education level [284, 313-317]; demographic factors such as gender and age [318, 319]; and bio-physical characteristics of the GI itself, including the type and size of GI, the location and perceptions of safety [307, 320, 321]. Additionally, it has outlined the potential barriers across the different demographics and how these barriers could differ over an individual's lifetime.

Examples of how this research could be capitalised on would include the development of support programs that encourage the development of non-permanent green walls that require minimal maintenance for owners and tenants. Other approaches could be targeted at encouraging different demographic groups to engage with more green initiatives, including GW implementation, and each approach could be tailored accordingly. This information should be of value to governments when developing and tailoring their support programs.

Once social acceptability was elucidated, implementation and feasibility were investigated in the final chapter (Chapter 6), with particular focus placed on green walls retrofitability in highly urbanised areas. The focus was placed on vertical greenery systems, commonly known as green walls (GWs), as they are a type of green infrastructure that is both an innovative and adaptive solution, enabling the reincorporation of vegetation in cities while minimising the competition for space/land allocation in an urban setting [377, 378].

Taking advantage of new or existing walls and the external sides of buildings in urban areas provides considerable potential for the construction of GWs on pre-existing structures, thus aiding in the amelioration of the problems facing cities with limited greenery [377, 378]. GWs can also simultaneously provide numerous positive outcomes for urbanised areas, such as increasing biodiversity and conservation [288, 290, 385], integrating climate change resilience with increasing vegetation, and improving air quality through deposition, sequestration, and biodegradation of air pollution [291-293, 386]. GWs have also been noted for their thermal insulation properties [387, 388], their ability to decrease the urban heat island effect, improved thermal comfort through evapotranspiration and improved protection from solar radiation while reducing buildings' energy consumption [13, 279, 282, 283]. Additional benefits associated with GWs include reduced noise pollution through increased sound absorption and decreased reverberation [24, 156, 160, 290, 294], increased aesthetic value of urban areas [389, 390], and improved mental health and well-being of residents [295-298]. Furthermore, these aforementioned benefits were explored, investigated or discussion throughout this body of research.

The implementation and feasibility of GW uptake in urbanised areas across Australia were explored through the development of an analytical tool for preliminary assessment, and the subsequent validation of this assessment tool in five major Australian cities demonstrated its effectiveness. The exclusionary set of criteria removed subjectivity from the assessment, ensuring it would be suitable for those looking to evaluate areas of interest and could be utilised by many stakeholders, from interested members of the public to government organisations, as it is not resource-intensive and does not require high levels of training. Furthermore, this tool could easily be utilised with readily available remote sensing techniques that are locally relevant to provide more detailed information and evaluation prior to site inspections. The evaluation tool's simplicity was designed with the intention of making an analytical method that is accessible to all within urbanised areas and enables comparison of the areas evaluated.

Future Directions

Despite these positive results, the current pool of research is incomplete and future studies should be considered. The determination of favourable plant species and substrate traits for both urban forestry and green infrastructure would greatly increase its application across a range of urban settings. Furthermore, the need for in situ implementation and validation would dramatically reduce the dearth of Australian centric knowledge. This additional research would elucidate what options or conditions could offer the best outcomes across all potential urban forestry benefits, such as mixed vegetation strategies to create interconnected urban ecosystems that give us a strong path forward to sustainable development and urban life.

Furthermore, this multifaceted body of research highlights the considerable effort we must undertake to address the adverse consequences of urbanisation, such as air pollution and noise pollution, across spatial and temporal mediums. While the evidence demonstrates urban forestry and urban greening's ability to provide sustainable solutions to our issues, we require more robust and adaptable policies, support systems, and guidelines to promote Australia's wider adoption and social acceptance of green infrastructure.

Developing dynamic urban greening strategies would also play a critical role in handling the temporal and spatial problems associated with one of Australia’s most detrimental urbanisation impacts, air pollution. The necessity for interconnected and mutually reinforcing standards that are both locally relevant and regionally adaptable will be vital if air pollution mitigation strategies are to be successful as urban development increases and extreme air pollution events become more frequent. Research into the impacts of different green policies and strategies employed by other nations or governments could provide a starting point for this future investigation. Additionally, given the delicate balance of our urban ecosystem, further investigation into the simultaneous environmental benefits provided by urban greening and urban forestry efforts would create stronger support for these green solutions and improve uptake and implementation.

This current body of research identified some of the greater barriers to community support and adoption as well as the appeal factors, which be explored further and leveraged to help engage the community. If utilised correctly, this information could also be crucial to future projects as it provides insight into community perception, understanding and perception previously unknown. While this exploratory survey was limited in scope, it also identified which groups amongst the populace were likely to be the most receptive to green initiatives, which features had the greatest appeal, and which were the greatest barriers to community support. This exploratory survey could also be expanded upon to help in the development of green initiatives as well as educational and marketing strategies. In particular, different demographic groups identified as less receptive to greening or less able to implement green solutions could be investigated further to overcome some of the more prominent barriers, such as the development of support programs for tenants and landlords to develop low maintenance and less permanent green wall structures. The development and expansion of this exploratory survey could also contribute to the previously discussed research above, as targeted surveys and investigations would simultaneously assist in understanding the impact of locally relevant approaches or strategies.

Finally, this research explored the practicality and feasibility of urban forestry and greening initiatives as organisations and governments aspire to align themselves with ambitious environmental goals of the future. It was found that Australia's three biggest cities, Sydney, Melbourne, and Brisbane, all had promising avenues for developing and supporting GW projects on a large scale. With the assistance of policy guidelines, incentives or greening requirements in new development could further assist in a rapid and effective adoption of GWs in these cities. The methodology of evaluating how viable urban greening projects could easily be repeated in other urban areas, allowing it to be used to examine potential projects by both public and private stakeholders. Further, this tool could be used alongside other pre-existing technologies to allow for more detailed evaluations prior to site inspections.

With this body of research complete, I look forward to starting my career as an academic so I can focus on investigating and exploring these projects further.

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